THERMOELECTRIC MATERIALS – DEVICES - SYSTEMS

Hi-Z 2000F

NSWC Sensor Generator

Final Report

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Introduction and Summary

This report presents the results of a preliminary program to develop a low power generator to power remotely located sensors. The generator is to use small changes (about 5^{o}C) in the ambient conditions to provide up to 1000 microwatts of power at 3.5 Volts. As an example, the generator would be attached to a structure, such as the hull of a ship, and utilize the difference in temperature between the ambient temperature within the compartment and the hull structure. Older structures or machines that produce heat within a ship's compartment can also be considered as heat sources, rather than a heat sink.

To achieve the power and voltage required, sufficient energy will have to be transferred from the surrounding ambient air to the generator via a natural convection heat exchanger. The energy will then be conducted through the thermoelectric module to the ship's hull, directly converting a portion of the energy to electricity.

A small demonstration generator was constructed during the study to verify the concept design. This generator utilized four existing thermoelectric modules which were developed for an existing DARPA program and demonstrates how both significant power and voltage can be generated with very low differential temperatures of 3-5^{o}C.

A second part of the study looked at the design of the actual sensor generator. The use of both bismuth telluride alloys as well as more advanced quantum well thermoelectric materials were considered. Estimates of the size of the sensor generators were made based on the thermoelectric materials used. The quantum well materials indicate large gains can be made with these more efficient materials.

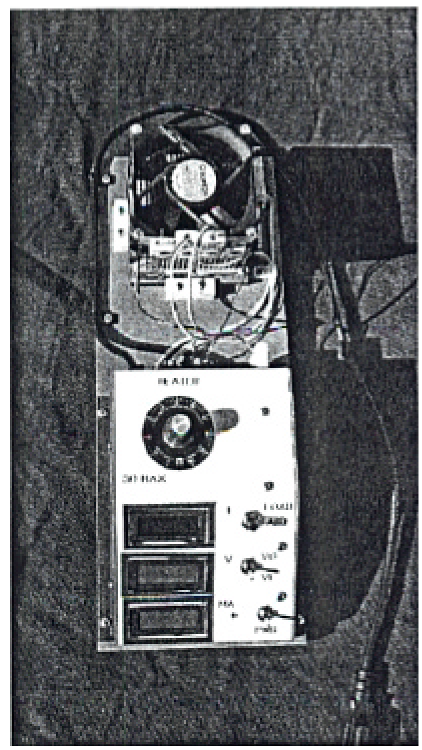
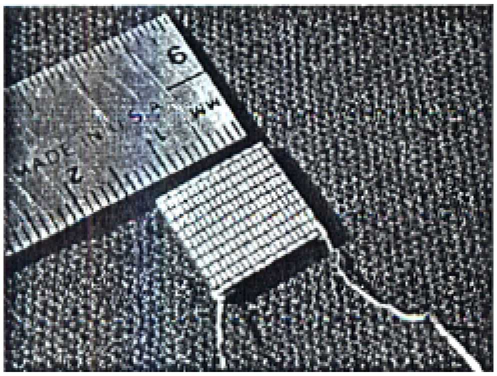


Figure 1 - Picture of Demonstration Generator**.**

Demonstration Generator System

A demonstration system for the NSWC thermal sensor generator has been designed and built. This system, as shown in Figure 1, incorporates a series connection of four of the modules which were designed to be used in the micro air vehicle (MAV) being developed for DARPA. These modules use a 16 by 16 array of N and P bismuth telluride alloy elements 0.5715 mm (0.0225 in.) on a side by 1.8796 mm (0.074 in.) long, bonded into a single structure that is 0.953 cm (0.375 in.) on a side by 1.8796 mm (0.074 in.) high as shown in Figure 2.



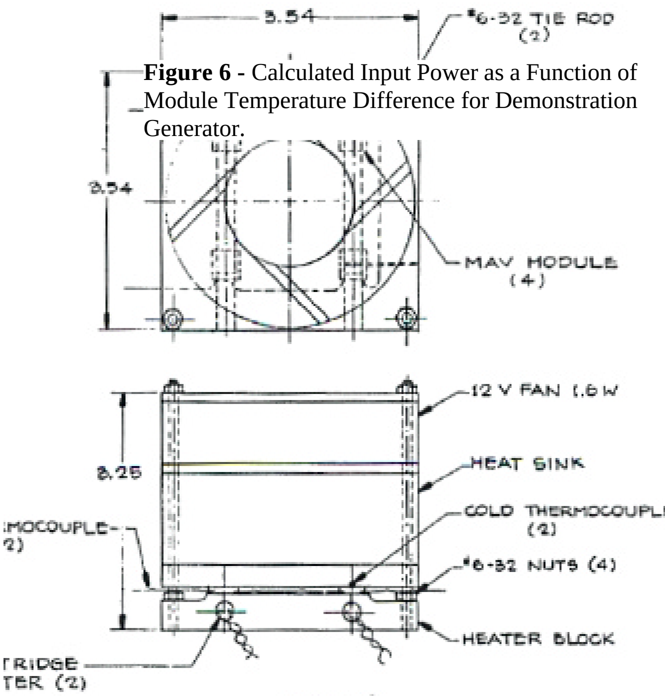


Figure 3

DEMONSTRATION GENERATOR

The array of four MAV modules, which provides a total of 512 couples, are evenly spaced between a copper heater block and an aluminum heat sink shown in the Figure 3 sketch. Both voltage and power output are a function of the temperature difference across the modules and the ratio of the electric resistance of the thermoelectric modules to the electric impedance of the load. Figure 4 shows test data for both the open circuit and matched load voltages as a function of the temperature difference across the module. It will be noted that the matched load voltage of 0.39 Volts for a temperature difference of 5°C is much lower than the 3.5 Volts desired in the final unit, but it is a verification that the concept is sounds. An output of 3.5 Volts requires either a much larger number of couples than available in the four MAV modules at 5°C delta T or a much higher delta T. To obtain the goal of 3.5 Volts at matched load for a 5°C difference, about 4000 couples is required and this is double in the next phase.

Figure 5 presents the matched load current and power output test data of the demonstration generator as a function of temperature difference across the module as measured by thermocouples placed on each side of the module. One will note that the output power of the demonstrator is in the milliwatt range, whereas it is only needed to be in the microwatt range in the desired sensor generator.

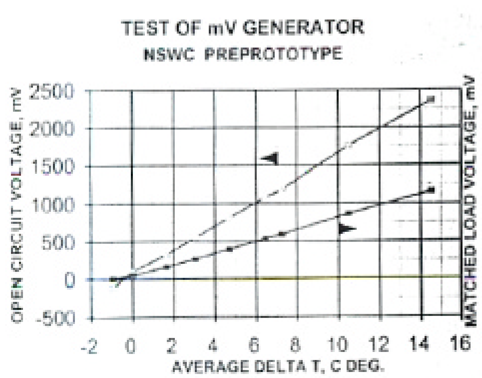


Figure 4 — Open Circuit and Matched Load Voltage As a Function of Module Differential Temperature—Test Data

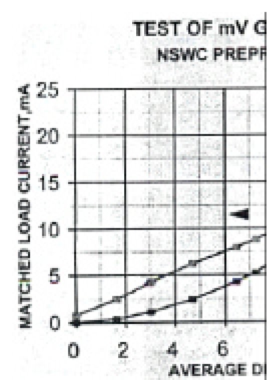
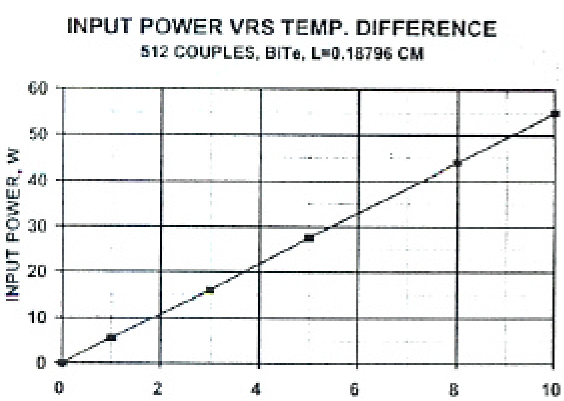


Figure 5 — Material Loa
a Function of Module Dif
Test Data.

The input power required for the demonstration generator is much higher than would

Figure 6 - Calculated Input Power as a Function of Module Temperature Difference for Demonstration Generator.



be required in the desired sensor generator. Figure 6 presents the calculated input power as a function of temperature difference across the four MAV modules. The heat sink cooling requirements are also much higher in the demonstration generator than the sensor generator because the heat sink must reject over 97% of the input heat. As a result, the demonstration generator uses an electric heat source to provide the input power and a fan-cooled heat sink, rather than a passive natural connection heat sink that will be used in the sensor generator.

The demonstration generator uses 110 V AC input to provide power to the two cartridge heaters in the copper heater block, a rheostat to control the current to the heaters, and a 12 V DC power supply to run the cooling fan.

Four type K thermocouples are installed in the demonstration unit, two in the heater block and two in the cold sink. These thermocouples are placed over the center of two of the four thermoelectric modules, as close to the module surface as practical. Small thermocouple read-outs are used to read the temperature across the module. Control of the heater input power is accomplished by manual adjustment of the large valuable resistor.

The electric output of the system is determined by measuring the terminal voltage of the modules and the voltage drop across one ohm shunt resistor using digital volt meters a variable resistance of up to 100 ohms represents the load. A single line drawing of the generator electric circuit is shown in Figure 7.

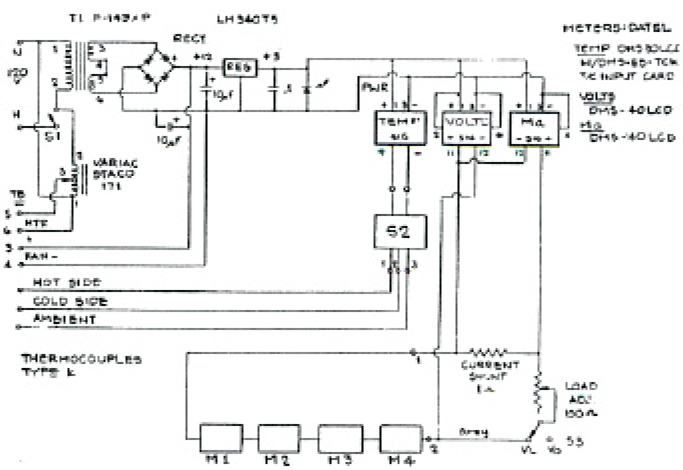


Figure 7 - Single Line for Demonstration Generator

The MAV type modules and the modules that will be used to form the sensor generator will be made of legs with the smallest dimension much less than one millimeter. Therefore, a different material fabricating process as well as a module forming process as well are used that is described in detail in reference 4.

The Bridgeman casting process is typically used to fabricate the N & P legs in bismuth telluride thermoelectric modules. However, when the smallest dimension of the legs must be less than about one millimeter, the Bridgeman process cannot be used because the typical flaw size in Bridgeman cast material is about one millimeter. When this limitation is encountered the higher strength fine grain, hot pressed material is used.

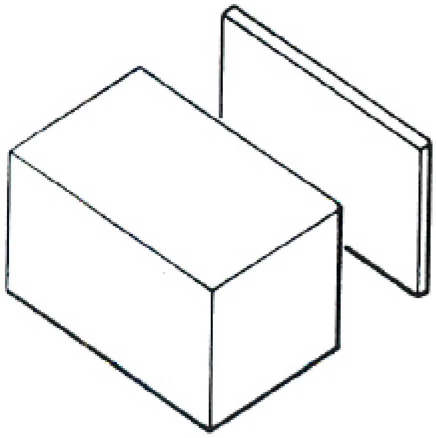


Figure 8 - Blocks of N and P $(BiSb)_2 (SeTe)_3$ are sliced into plates.

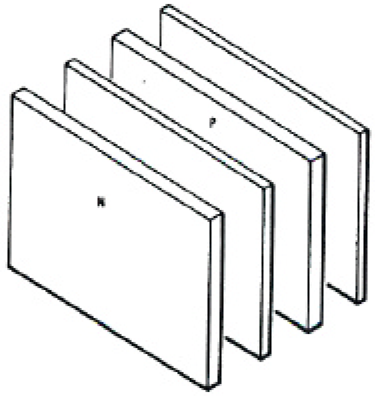


Figure 9 - The N and P plates from Figure 8 are alternately stacked with self-bonding Kapton® between the plates

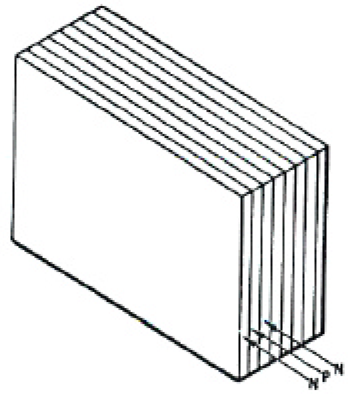


Figure 10 - The plates and Kapton® are bonded into one composite.

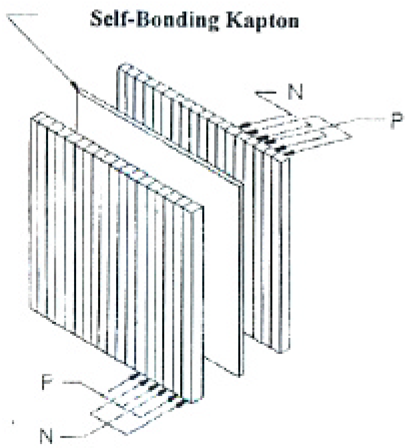


Figure 11 – The stack of Figure 10 is Sliced to form plates of N and P elements. The plates are alternately layered with a 1 mil layer of self-bonding Kapton®.

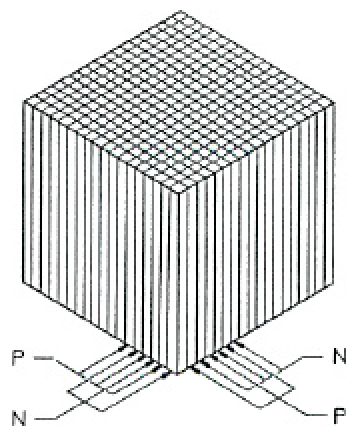


Figure 12 – The assembly of Figure 11 is bonded into an array of 324 elements. The matrix is then cut and lapped to length.

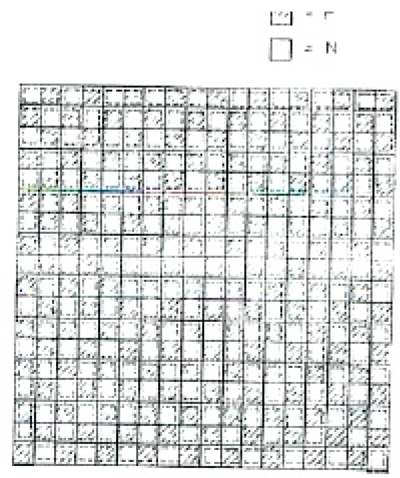
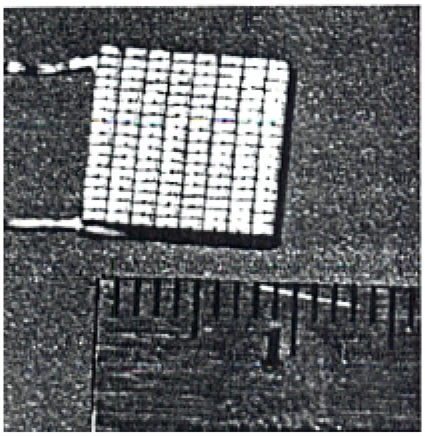


Figure 13 - A mask is laid over the matrix and Au is deposited to join the N and P elements in a series circuit.

The module assembly process shown in Figure 8 thru 13 starts with vacuum hot pressing relatively large blocks of fine gram P and N type bismuth telluride alloy. The powder metallurgy-prepared blocks are oriented so that the material is sliced perpendicular to the pressing direction. The bismuth telluride type alloys are anisotropic (especially the N material) and the most favorable direction is perpendicular to the pressing direction. For Bridgeman cast material, the favorable direction is parallel to the direction of growth as shown in Figure 8.

A satisfactory assembly or matrix is produced when the mask used for depositing the Au (by evaporation) can be aligned without shorting any matrix elements. Typical problems while can be encountered if the necessary precautions are not taken are:

1. Spacing between the elements was not consistent.



2. Rows of elements were not parallel.
3. The slices and plates varied slightly in thickness.

Error accumulation (or tolerance build up) in stacking in module with a large number of elements can cause the misalignment. This condition cannot be permitted because the overlay mask used for evaporation of the contacts will then not align properly to produce the desired circuitry.

The amount of allowable misaligmnent is less than 10 mils over the width of the modules. Thus, the tolerance level on each component must be controlled to less than 0.1 mils to obtain acceptable assemblies.

Figure 14 - Micro Air Vehicle module i 16 X 16 array of 0.5715 mm square le Module is 0.070" thick and produces (Watts at 5V at 200°C temperatu difference.

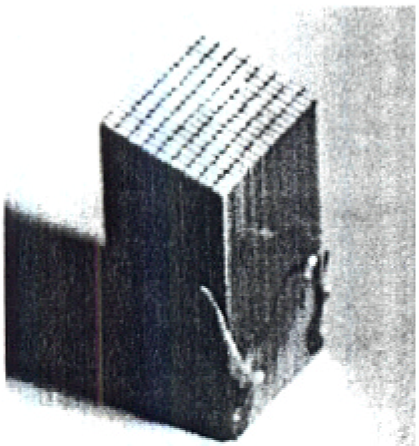


Figure 15 - 40mW 5V Module for Space Applications. Contains 324 legs 0.381 mm square and 22.86 mm long in an 18 X 18 array.

Three approaches can be taken that proved larger modules with satisfactory dimensional tolerances:

1. Assemble smaller portions of the module at one time and then join these sub-modules together.
2. Modify the existing tooling to afford better alignment of the elements.
3. Specify slices with less thickness tolerances.

It should be noted that the MAV modules used in the demonstration generator use welded Au contacts, not deposited contacts. The welded contacts are used for MAV because it is designed to handle much higher currents than the sensor generator.

The initial joining of the N and P elements into a series circuit for each stage is accomplished by evaporating a layer of Au through a mask. The mask openings formed the series circuit. A typical coating layout for an 18 x 18 array, such as used in the 40 mW module, was shown in Figure 13.

Shown in Figs. 14, 15, and 16 are photographs of completed modules with 0.5715mm square, 0.381mm square and 0.254mm square legs respectively with Au contacts. For the modules with 0.381mm square and 0.254mm square legs, (their length is relatively long) the resistance of the legs is quite high, thus, only a few microns of Au are required for the electrical contacts to make the extraneous circuit resistance negligible.

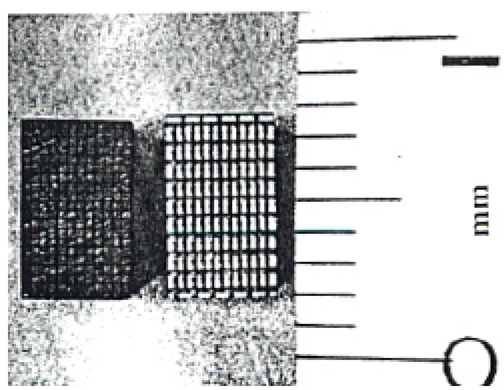


Figure 16 - Module contains 240 elements in a 20 x 12 matrix. The elements are 0.254 mm square on cross section. Module is shown with (left) and without (right) contacts.

The 0.5715mm square elements used in the MAV modules are relatively short and their resistance is quite low. It is therefore desirable to have relatively thick Au contacts for joining the N and P elements and thereby minimize the extraneous circuit resistance. Thicker contacts can also endure more rugged handling and is being pursued for the DOE and DARPA modules.

Sensor Generator Module Sizing Using Bi_2Te_3 Based Alloys

Figure 17 presents a graph of matched load voltage as a function number of couples for a delta T of 5^{o}C and I O^{o}C. One can see that approximately 4500 couples is required to reach 3.5 Volts at matched load with a 5 C^o difference across the module. The selection of 4608 was made to achieve an even set of modules which would consist of four sub modules with an array of 48 by 48 elements.

Figure 18 presents the matched load power for 4608 couples of various element dimensions with a 5 C^o temperature difference as a function of the element length. One can see that to reach a desired output of less than 1000 microwatts, one would either have to use a very small cross-section element or a larger cross-section element with a long length.

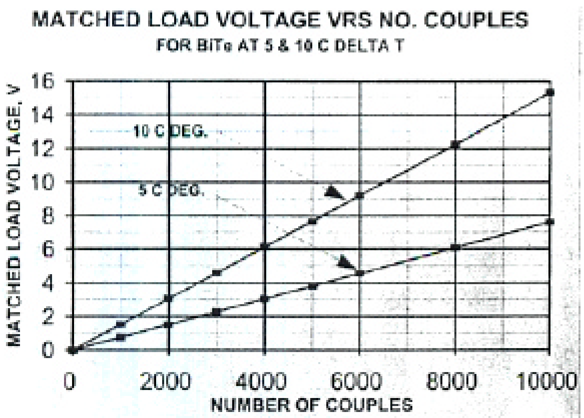


Figure 17 - Calculated Matched Load Voltage as a Function of Number of Couple for 5 and 10^{O}C bifferential Temperature.

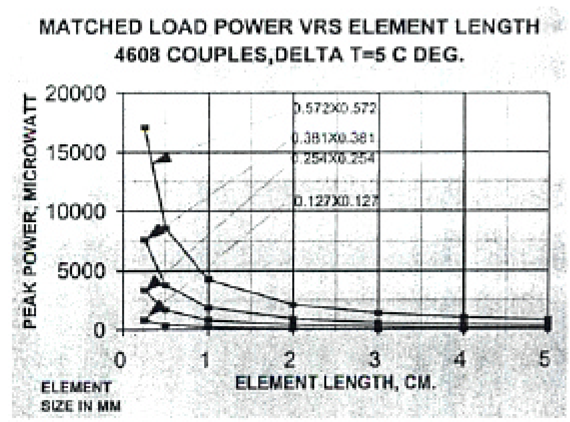


Figure 18 - Calculated Matched Load Power as a Function of Element Length for Several Square Element Sizes.

The argument against very small cross-section elements made by slicing is both that the percentage of material loss in cutting increases and the cost of accurately fabricating the contacts increases as the element cross-section is decreased. Both lead to higher module cost per Watt as the element size decreases. Also, the heat flux through the module increases as the cross section decreases which creates additional temperature drop at the module interfaces.

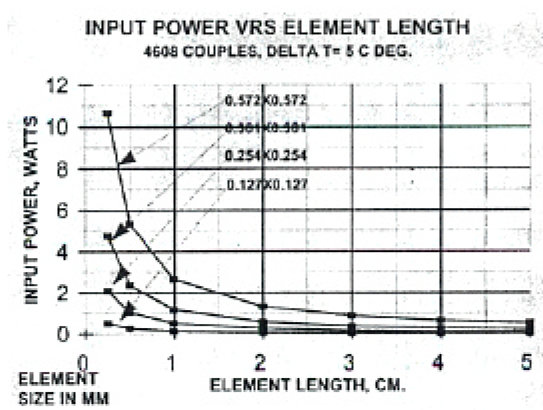


Figure 19 - Input Power as a Function of Element Length for a 4608 Couple Module of Various Sized Elements at a differentiated Temperature of 5^{o}C.

On the other hand, the amount of material required to fabricate a module with larger elements will also require more material because they must be relatively long to have an output power below 1 milliwatt at 5^{o}C difference. Figure 19 presents the input power required by 4608 couple modules various element sizes as a function of element length.

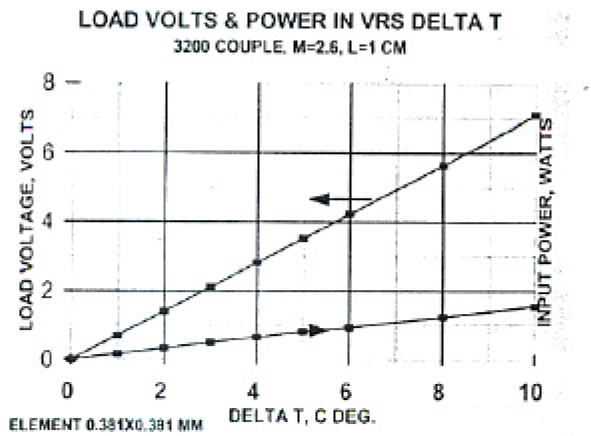


Figure 20 - Calculate Load Voltage and Input Power Function of Module Differential Temperature For a 3200 Couple Module Operating At a Matching Factor of 2.6.

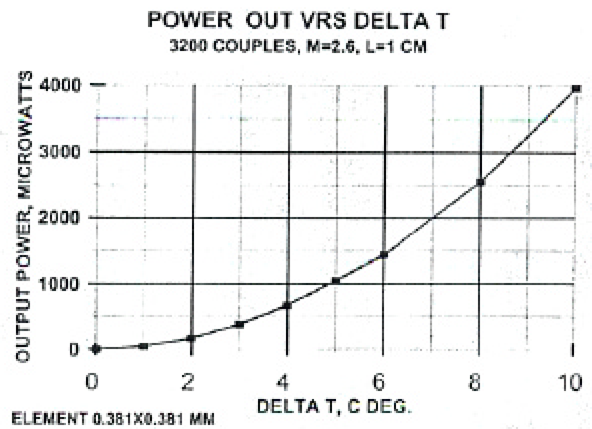


Figure 21 - Calculated Output Power as a Function of as a Module Differential Temperature For a 3200 Couple 1 cm Thick Module Operating at a Load Matching Factor of 2.6.

One can see that on can achieve an input power of 1 Watt or less with element lengths of up to 2.7 cm for the element dimensions investigated.

One would like to minimize the input power required to achieve the desired electrical output. A goal for an input power of less than 1 Watt has been set to keep the volume of the heat exchanger to a minimum.

An alternative method to obtain the desired voltage and power and minimize the cost of the module is to operate the generator off of matched load. Operating the generator off of matched load results in a module with fewer, larger elements and less length.

Figure 20 presents curves of load voltage and input power for a module with 3200 bismuth telluride alloy couples. This module has elements which are 0.381 mm square by 1 cm long. The curve is for operating at a load matching factor of 2.6, i.e. the impedance of the load is 2.6 times the resistance of the module.

One can see from Figure 20 that the input power required is 0.823 Watts and the output voltage is at 3.5 Volts. Figure 21 presents the output power as a function of temperature difference across the module and this curve shows that an output power of 1000 microwatts can be obtained from this module at a 5 C^{o} temperature difference. If less than 1000 microwatts output is desired, the elements can be made longer which will reduce the heat exchanger size.

The 3200 couple module would consist of four sub-modules with a 40 x 40 array of elements. The 0.381 mm square elements required are the same size as the elements used in the 40 mW module shown in Figure 15 which Hi-Z is currently fabricating under contract to DOE. The 40 mW modules uses and 18 x 18 array of elements 2.286 cm long, providing Hi-Z experience making the electric contacts on this size element.

Sizing Generator Using Silicon Based Alloys

The use of doped silicon was considered for use in the sensor generator because the Seebeck coefficient for these materials can be five to ten times higher than the Seebeck for bismuth telluride alloys. This higher Seebeck would therefore lead to the use of fewer couples to achieve the desired 3.5 volt output. However, the electric resistivity of lightly doped silicon is much too high and results in an heat-to-electric conversion efficiency which is much lower than can be achieved using bismuth telluride alloys operating over the same temperature difference.

Because of the lower efficiency of silicon modules, the heat exchanger for a system would have to be orders of magnitude larger than that for a system using bismuth telluride alloys. Doped silicon has therefore been dropped from further consideration.

Sensor Generator Sizing Using Quantum Well Films

Hi-Z Technology has been developing multi-layer quantum well films (MLQWF) for the past several years. These films are made by sputtering alternating thin layers, about 100 Angstrom, of two materials which have differing band gaps. A thermoelectric couple would consist of joining films of P type material and N type material in the same way that conventional thermoelectric modules are fabricated.

At the present time, Hi-Z has developed films made of alternating layers of P type silicon-germanium and silicon, N type silicon-germanium and silicon and alternating layers of two types of boron carbon alloy, B_4C and B_9C which is always P type.

Simple 1, 2 and 4 couple thermoelectric devices, such as shown in Figure 22, have been fabricated and tested. The test results indicate that devices made from these films should have performances that are significantly better than those of conventional thermoelectric materials such as the bismuth telluride.

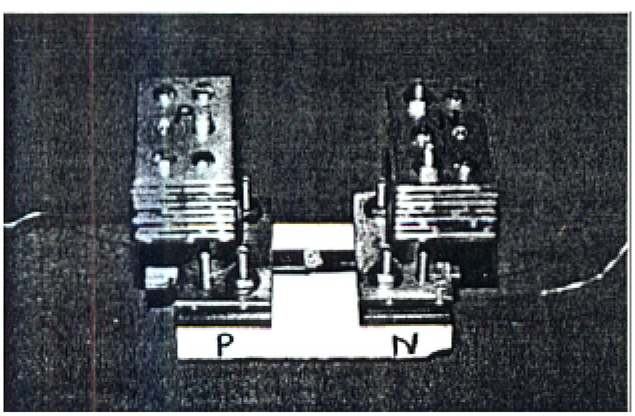


Figure 22 - Experimental MLQWF Couple

The development of methods to manufacture and characterization these films is a current on-going effort at Hi-Z. We are currently under contract to the Department of Energy, DoE, to fabricate the first module using MLQWF[(3)]. This effort started in August 2000 and is currently scheduled to be completed in August 2002.

While voltage and current in a MLQWF device was obtained from the simple couple test, it was impossible to directly determine efficiency in this device. The module being developed under the current DOE program will allow us to determine all the module performance parameters, including conversion efficiency.

The MLQWF couple that was selected for the NSWC sensor generator module consists of one leg of P type B_4C/B_9C and the other leg of N type Si/SiGe film. The particular combination was chosen because it is one of the combinations used in the simple couple test.

Another combination that might also be considered would be a module made of couples made of P and N type Si/SiGe films.

The following materials parameters for the films were used in the sensor generator module design:

	P: B_4C/B_9C	N: Si/SiGe
Seekbeck	500uV/^{O}C	-920uV/^{O}C
Resistivity	340 u ohm-cm	900 u ohm-cm
Thermal Conductivity	0.03 w/cm^{o}C	0.0135 w/cm^{o}C

These parameters represent the values obtained from test data for the MLQWF operating between a T_c of 20^{o}C and a $T_H$of 25^{o}C. A module was sized using an arbitrary value of 1 cm for the element length. It was also assumed that the cross sectional area ofboth the N and P elements would be equal, although this is not necessarily required.

Element Size	0.0157 X 0.0157 X 1 cm
Number of Couples	728
Matrix	38 X 38 Elements
Load Voltage	3.5 Volts
Module Power	1000 uw
Heat Flux	0.341 w/cm^2
Matching Ratio	3.02
Conversion Efficiency	0.8204%
Input Power	0.122 W
Current	286 uA
Module Resistance	5410 ohm

It can be easily seen from the preceding data that the number of couples requir6d to achieve 3.5 Volts and the input power of 0.122W required to achieve the 1000 uW output are significantly lower than for the BiTe module. This means that when the MLQVVF materials are fully developed a generator using elements as described here should be less expensive to produce both because the number of couples in the module will be lower and the size of the heat exchanger will also be much smaller.

Air Side Heat Exchange

The heat transferred on the air side of the sensor generator must be achieved using passive natural convection heat transfer. In this case, the amount of heat transferred is dependent on fin spacing and geometry.

Optimum fin (cooling channel) spacing, D_{opt}**,** can be shown for vertical fins to a function of fin height, H, and is determined by the equation:

$$D_{opt} \sim 2.3 * H * Ra_H^{1/2}$$

where Ra_H is the Rayliegh number based on the fin vertical height and is a function of the air properties at the temperature in question as well as the vertical height of the fin or cooling channel, H, and the temperature drops across the boundary layer film.[1]

The optimum spacing, D_{opt}**,** required to transfer the heat into or out of the sensor generator is typically between 1 and 2 cm for a reasonably sized heat exchanger. A heat exchanger for the BiTe generator is required to transfer 0.822 Watts while keeping the temperature drop from the ambient to the surface significantly less than 1^oC will be about of 24 cm square by about 6 cm deep with fin spacing of about 1.5 cm. One of the tasks during the next phase will be to optimize the size of the air side heat exchanger with respect to volume, weight, and cost.

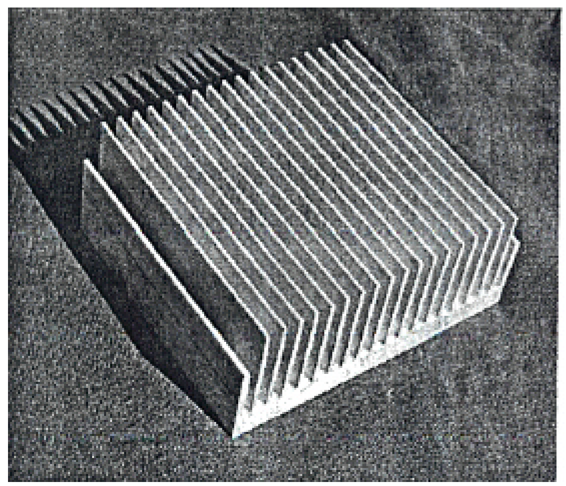


Figure 23 - Extruded Heat Exchanger

The heat exchanger for the sensor generator using a module made of MLQWF elements would be required to transfer only 0.122 Watts to produce 1000uWatts of output. This will require a heat sink that is about 9 cm square by 4 cm deep with fins spaced at about 1.25 cm apart.

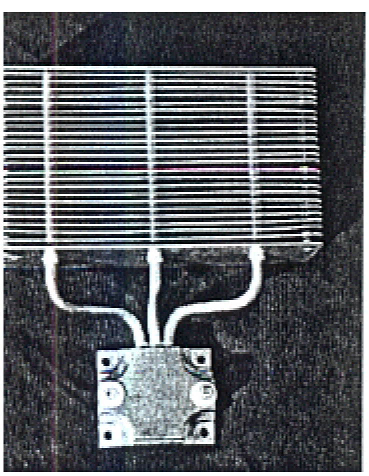


Figure 24 - Heat Pipe Heat Exchanger

There are two approaches to the design of the heat exchanger. The first is to use a solid heat exchanger, such as shown in Figure 23, which could be fabricated by machining, extrusion, casting, or brazing or other techniques on which submodules are uniformly spaced. The second approach would be to incorporate a heat pipe heat exchanger which transfers the heat from a closely spaced set of modules to a dispensed set of natural convection fins such as shown in Figure 24.

One of the considerations in choosing between the two heat exchanger approaches will be the transient response characteristics of the generator. The single solid heat exchanger approach tends to have a greater mass than the heat pipe system and therefore may respond less rapidly to changes in ambient temperature. On the other hand, the lower mass heat pipe approach has a number of thermal interfaces which may result in increased temperature difference between the ambient temperature and the modules and require that the air side heat exchanger area be increased to compensate for these extra temperature drops. There is very little data available from heat pipe manufactures regarding the operation of heat pipes with temperature differences of 1^oC or less, as would be required for the sensor generator.

It will require some experimental work with heat pipes operating in this low temperature difference range before a heat pipe heat exchanger can be recommended for the sensor generator application. A paper by Snyder on miniature embedded heat pipes suggest that there is an activation energy of the order of 10 Watts associated with micro heat pipes operating near ambient temperature. The consensus is that such and activation energy could result in a high (relative to 5^oC) temperature drop which may render the heat pipe unusable in the sensor generator application since the generator requires and input power of less than 1 Watt.

Closure

1. The demonstration generator test results show that significant voltage and power can be obtained at very low temperature differences (3 to 5^oC) even though the thermoelectric modules available for use in the generator were not optimum.

2. Calculations show that a bismuth telluride alloy based thermoelectric module with 3200 couples can provide the 1000 uW at 3.5 volts required by operating the module off matched load. Such a module can be built today using currently available technology.

3. Modules made using MLQWF (Multilayer Quantum Well Films) technology hold the promise of building smaller and less expensive sensor generators. The technology for these devices will be available in about three years.

4. Heat exchange with the ambient can be achieved using a reasonably sized natural convection heat exchanger. The heat exchanger required for the sensor using MLQWF modules will be smaller and lighter then that required for the same power output using conventional bismuth telluride alloy modules.

5. The heat pipe exchanger has potential weight and response time advantages over a solid heat exchanger. However, additional testing will be required to resolve its characteristics when operating at low power and temperature differences before a heat pipe system can be recommended.

Works Cited

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Diesel and Propane Fire Test Report

Summary

Scanning Receiver scans were taken through diesel and propane fires between two PADs equipped with diamond dipole antennas on Thursday, July 19th at the University of Maryland Fire Rescue Department. This was done while a class was being held to instruct firefighters how to extinguish these types of fires. The propane fire data was obtained in a nearly ideal data collection environment. The diesel fire data was more difficult to collect because the fire was mainly burning on an oil truck, which the radios could not communicate through, and because fire fighters were constantly moving in and out of the scene. Neither type of fire seemed to affect the signals much, although this statement is simply from visual analysis of the waveforms and not from any quantitative analysis.

Location, Time and Contact Information

Testers:	Ben Lonske and Yalin Hou
Date:	Thursday, July 19th, 2001
Place:	University of Maryland Fire Rescue Department 4500 Paint Branch Pkwy Chevy Chase, MD
Contact:	Steve Carter or Ray (301) 226-9994

Setup and Procedure Common to Both Fires

Setup

The two radios were used were 200-series PADs 295 and 252. They both used the diamond dipole antennas. PAD 295 was used as the requestor and PAD 252 as the responder. They both have homebrew firmware version 2.0j. Scanning receiver compiled on 6/18/01 was used. The PADs were on carts provided by the staff at the fire department and were approximately 4 feet and 5 feet off the ground respectively.

Procedure

Data was collected before any fire was started (and with no people in the way) for a baseline, and then after that whenever large amount of flames, smoke, and/or steam were present. For each of these selected instances of time we simultaneously did a scan with Scanning Receive and took a picture with the digital camera. We then saved a screen shot of the Scanning Receiver scan in a Word document and saved the raw data of scan data in a .dat file. That way, three pieces of data were collected for each selected instance (photo, screenshot, and raw data file).

Caveats

The testers believe the following caveats should be kept in mind in regard to both fires:

- Fire, steam and smoke conditions change rapidly. Our method of simultaneously scanning and taking the digital picture ("OK…Now!") probably only had synchronization accuracy of about a second. Moreover, Scanning Receiver takes about two seconds to return a scan, and it is unclear exactly when during that time the data is captured. The testers believe this caveat only really affected the diesel data. This is because the propane fireballs, while constantly changing in character, completely occluded the responder and a large area around it for many seconds at a time.
- The digital camera photos were not taken from exactly the point of view of the requester antenna, but from the right maybe a foot.

Additional Data and Location of Data

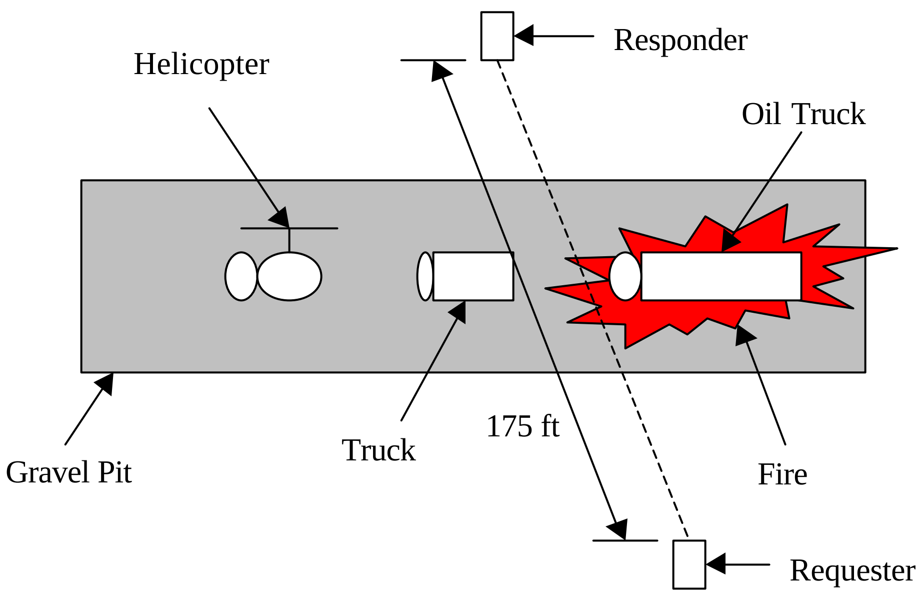
Not all the data that was collected if shown, only what is deemed the most representative and more useful for final reports of proposals. To see other photos or screenshots, or any of the data files, look in the **UWB Test Data** directory of Ben Lonske's computer (IAI17). All this data is also contains in the zip file entitled *Diesel and Propane.zip*

Diesel Fire

Scene

The scene for the diesel test looked as follows. There was large gravel pit with full size vehicles in it used for fire training – an oil truck, a truck, and a helicopter. During the training, Type 2 diesel fuel would seep out of one of the three vehicles and a person would ignite it. Once there was a sufficient fire on the vehicle, people in the class would move in an extinguish it. This was repeated seven or eight times. During this particular class, fires were set on both the tanker truck and the helicopter, but only the tanker data is shown here, as we were never able to scan though any flame or significant smoke with the helicopter.

We were rather limited as to where we could place the PADs during this test for two reasons. First, the leader of the class wanted our equipment to be in certain areas so that: 1) it would not be in the way of the people in the class and the hoses, and so that 2) it wouldn't risk getting burnt or wet. Second, we were not able to get a signal through any of the vehicles, so we had to scan across them. We scanned across the front of the tanker, with a distance from requester to responder of 175ft. Here is a diagram of the setup we used:



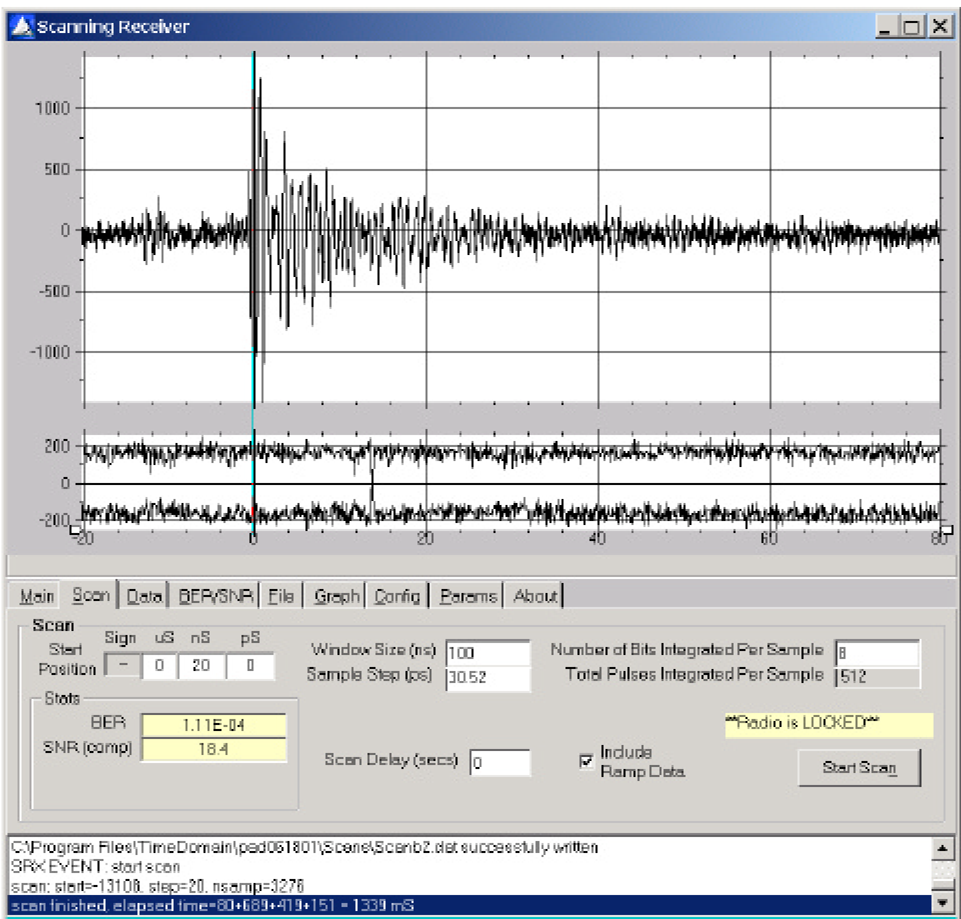
Data

The following pages have photos and screenshot pairs of the data collected during the diesel fire. The pictures are being taken from the point of view of the requester. Note that the signal to noise ratio is low in all cases – we believe this is mostly because of the distance, but also because of the vehicles to either side of the signal. We tried to scan even closer to across the edge of the truck, but found the signal degraded to the point where we could not reliably stay locked.

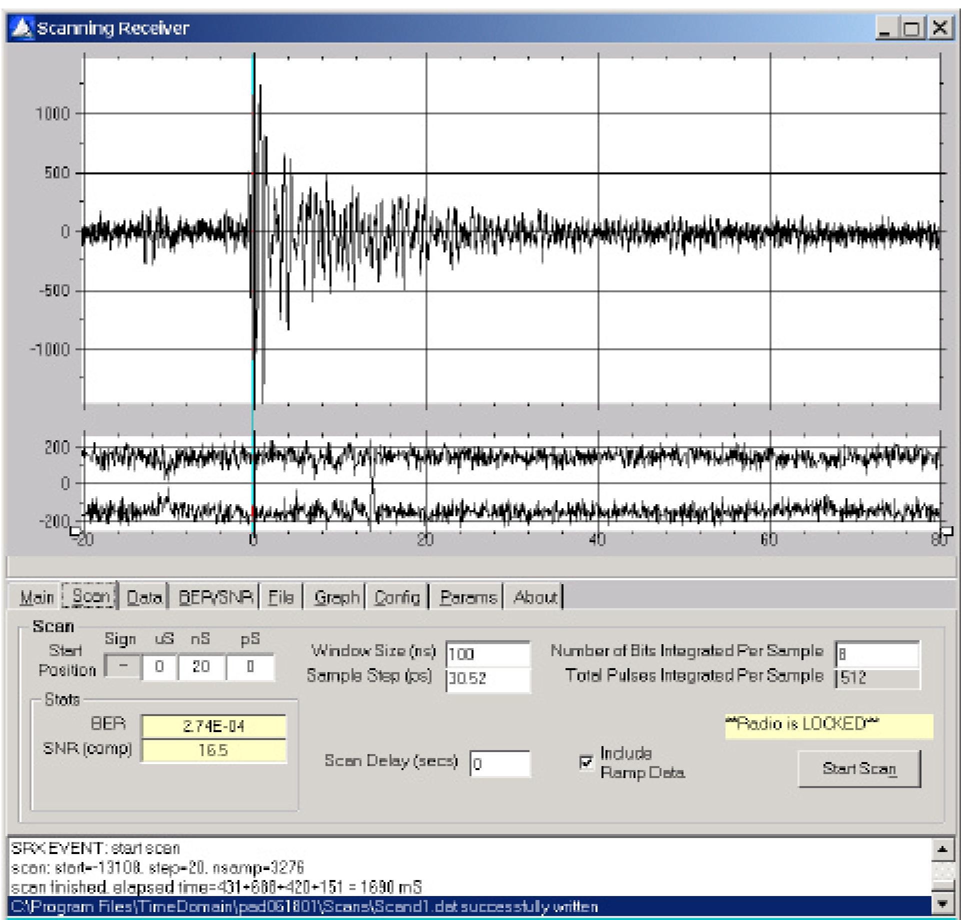
The testers believe the following additional caveat should be kept in mind in regard to the diesel data:

- The same lock could not be maintained throughout the diesel fires, since fire fighters getting in the way of the signal would sometimes (but not always) cause Scanning Receiver to re-lock. This makes the signals and SNRs collected not easily comparable.

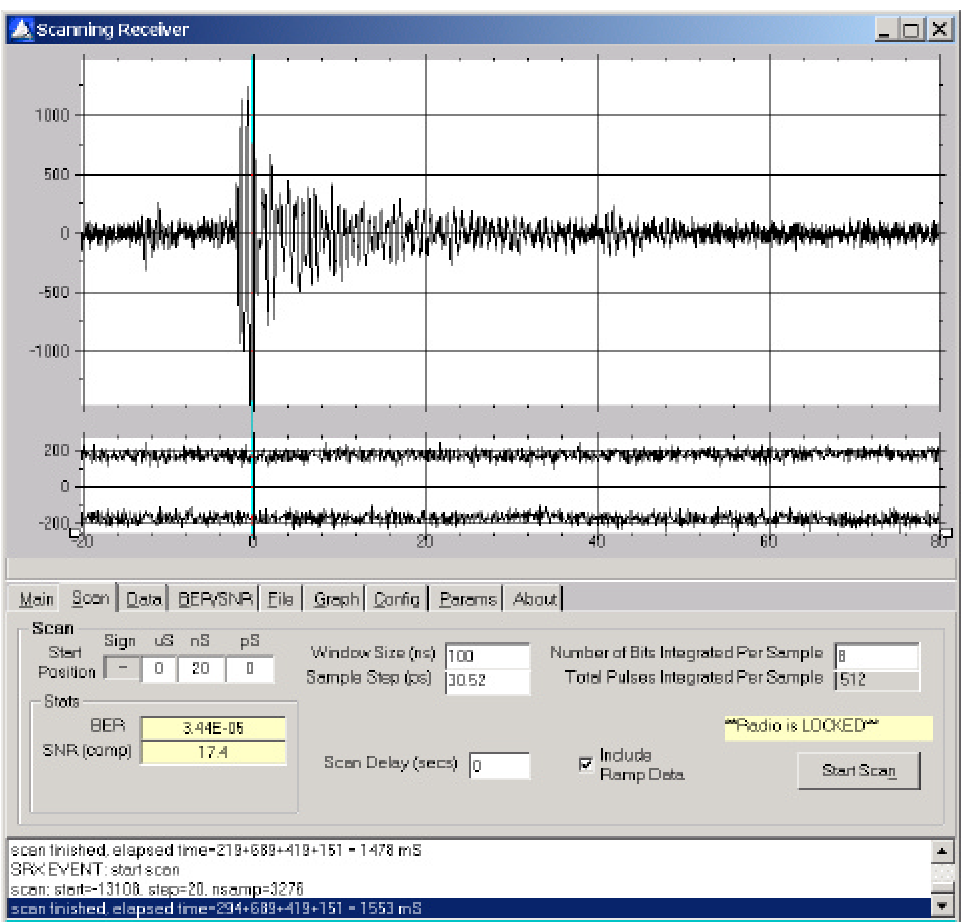
Before diesel fires:



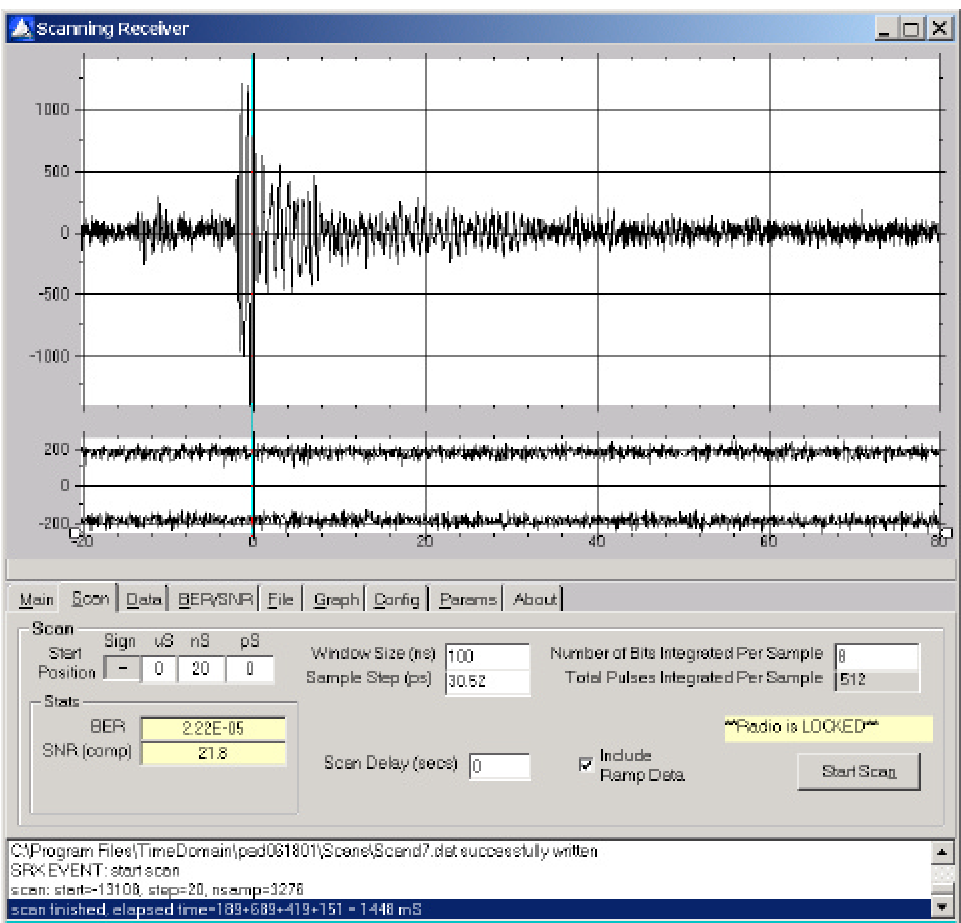
Tanker burning near, but not obstructing, line of site:



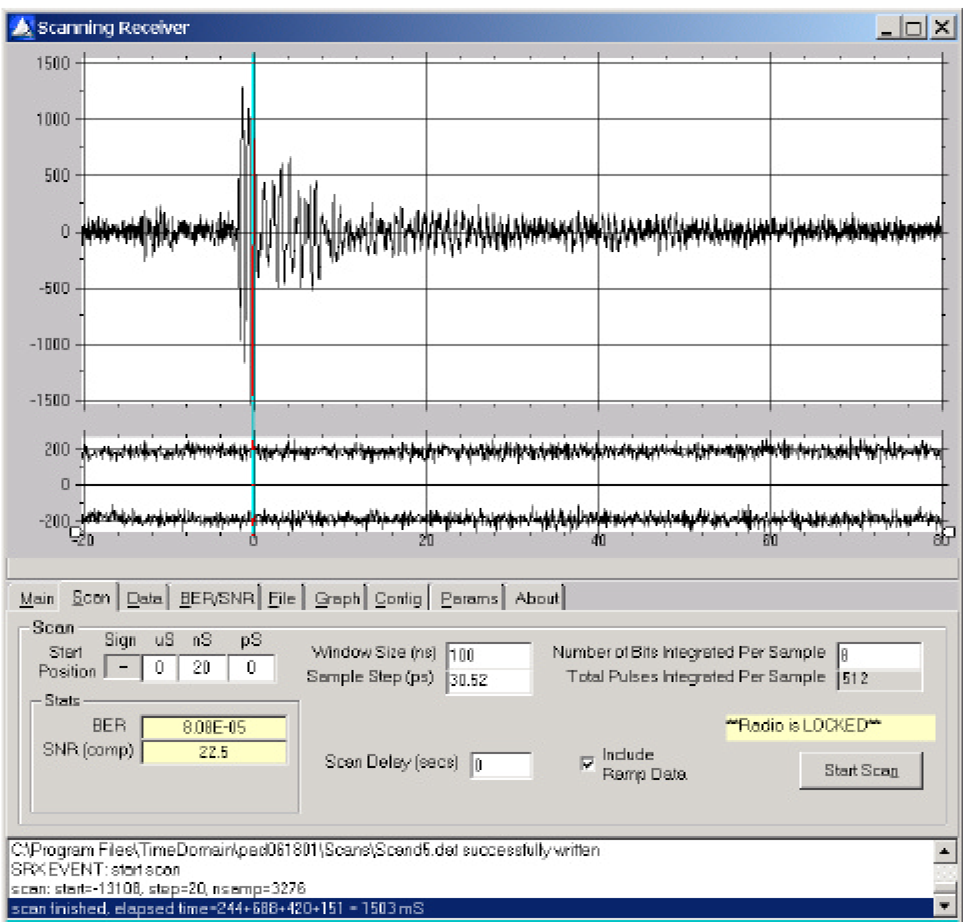
Best scan through flames:



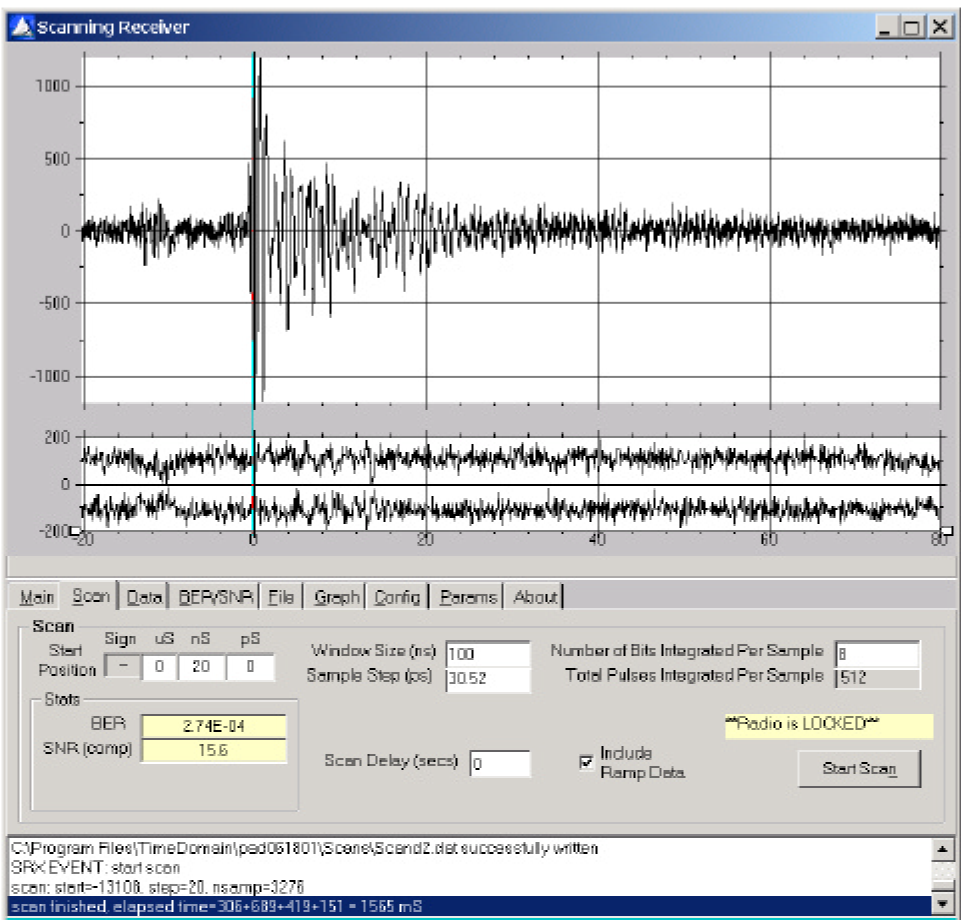
Steam, plus water and flame near line-of-sight:



Steam and smoke:



Four men on left:

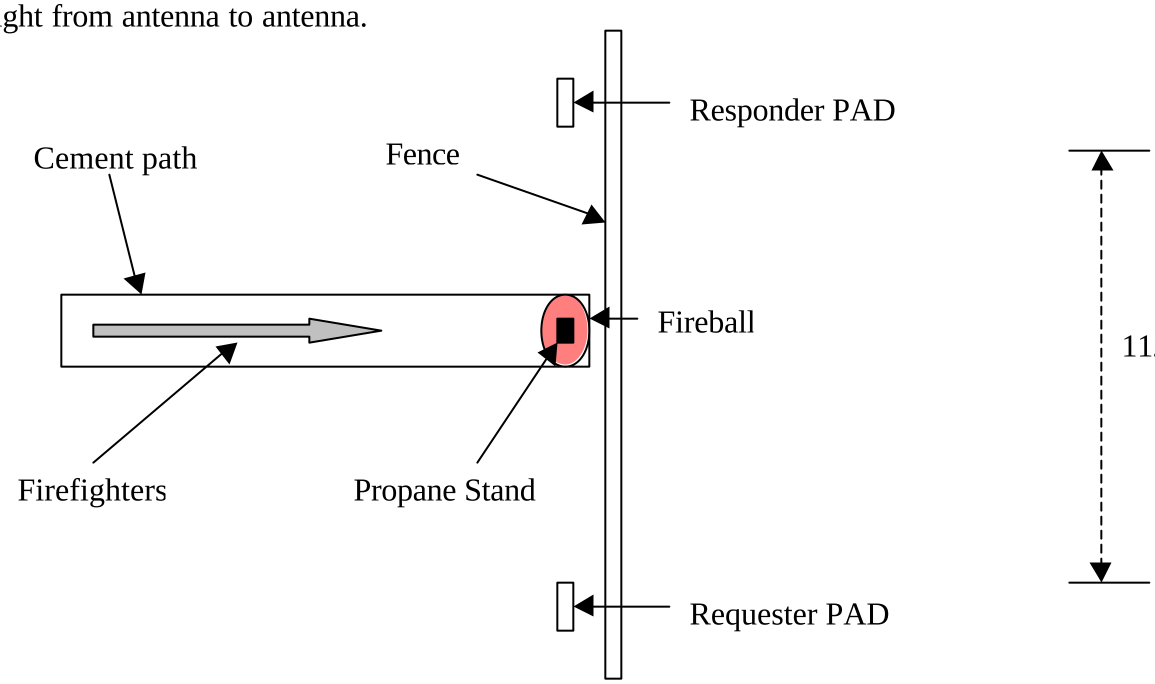


Propane Fire

Scene

The scene for the propane test looked as follows. There was a stand, approximately three feet in height, that stood in front of a chain-link fence. Propane was turned on to come out of the stand, was ignited, and was then turned up until a large fireball was created. The firefighters approached the stand in two lines along a cement path that was perpendicular to the fence. Each line of trainees carried a hose that was kept spraying at the fire with the goal of taming it enough that a third person standing in the middle of the two lines could twist a shutoff value located at the base of the propane stand. They then backed away from the propane stand along the cement path. This was repeated four or five times.

As shown in the diagram below, the two PAD's were setup up alongside the fence (about five feet away from it), perpendicular to the approach of the firefighters. The distance from one PAD to the other was 112 feet, with the propane stand approximately in the middle. As can be seen from the first photo, the PADs were high enough so that the propane stand was not in the way of the line-of-sight from antenna to antenna.



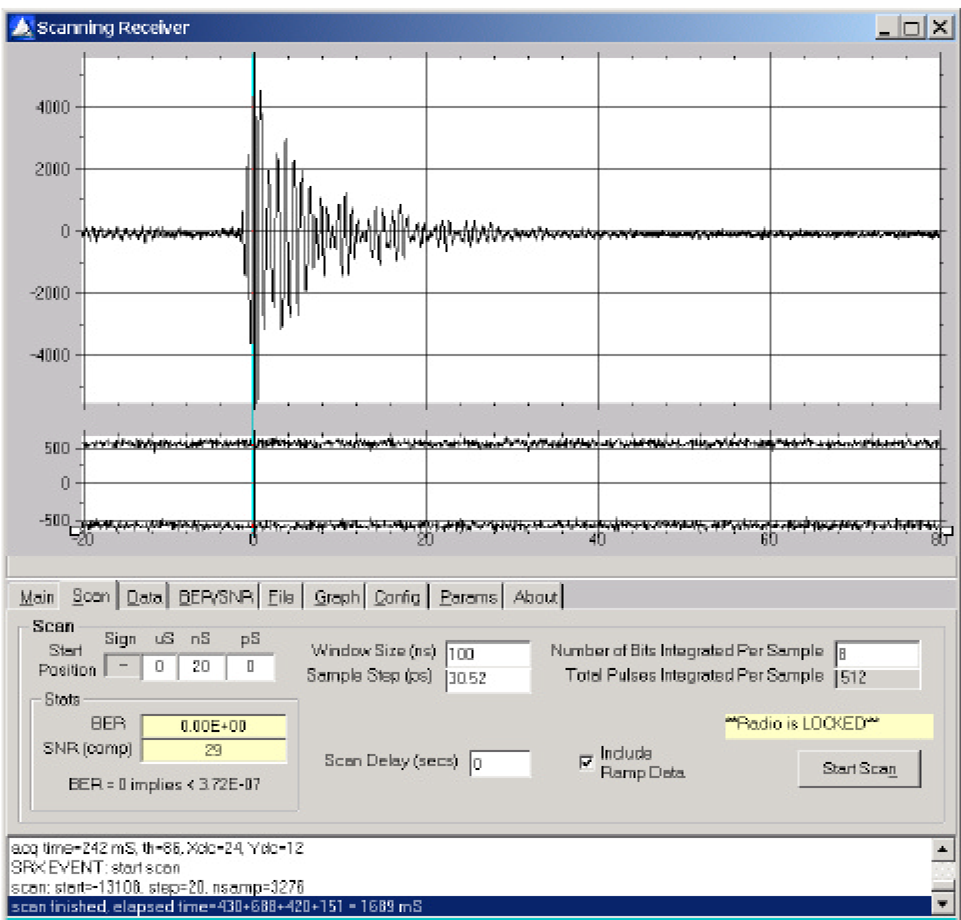
Data

The following pages have photos and screenshot pairs of the data collected during the propane fire. The pictures are being taken from the point of view of the requester. The testers believe this data was collected in almost ideal conditions, as:

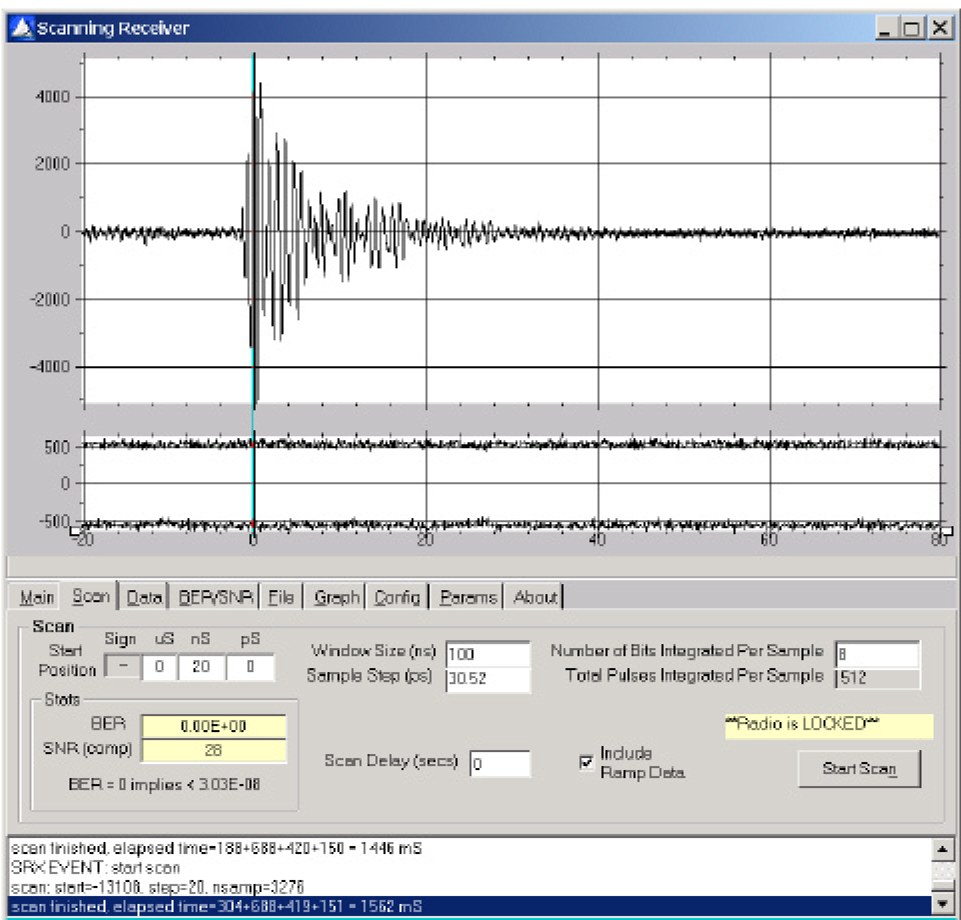
- The same lock was maintained for all the data.
- The scans were made directly through the middle of the flames
- The firefighters did not get in the way of the scans (except the extra one entitled "spray practice").

- The only difference between the no fire and fire scans was some additional water on the ground, which probably made little or no difference to the scan data.

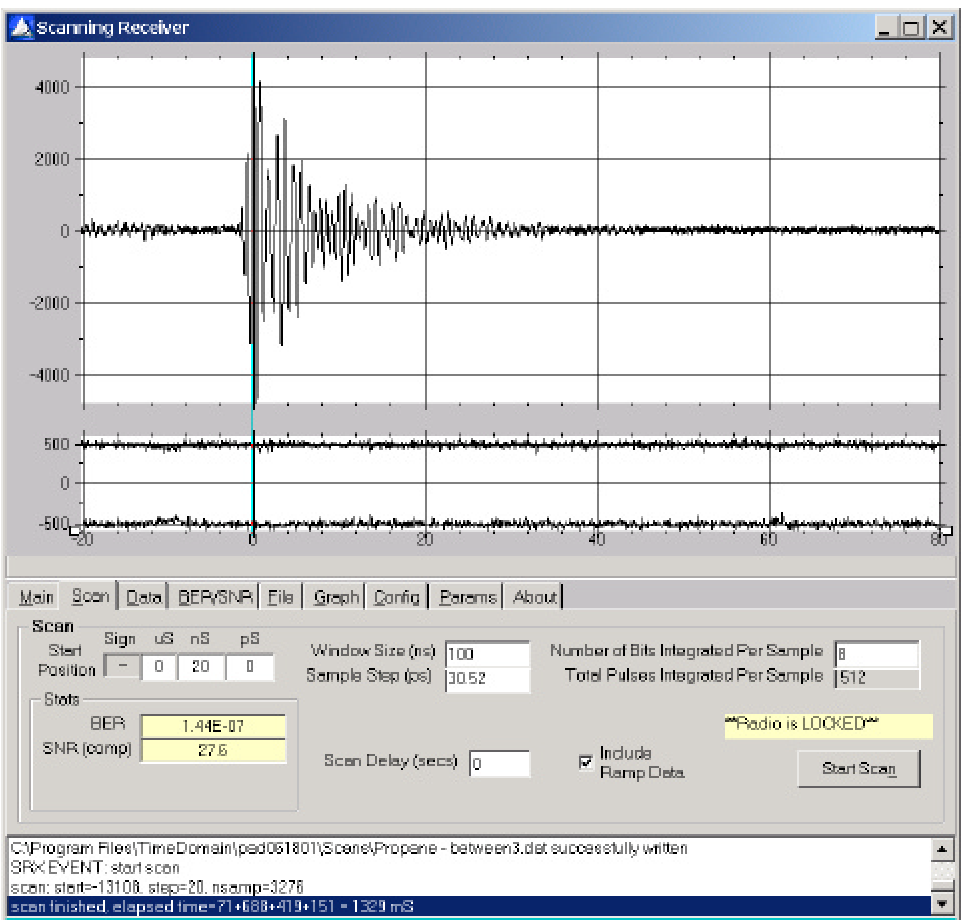
Before propane fires (two other scans can be found in data directory):



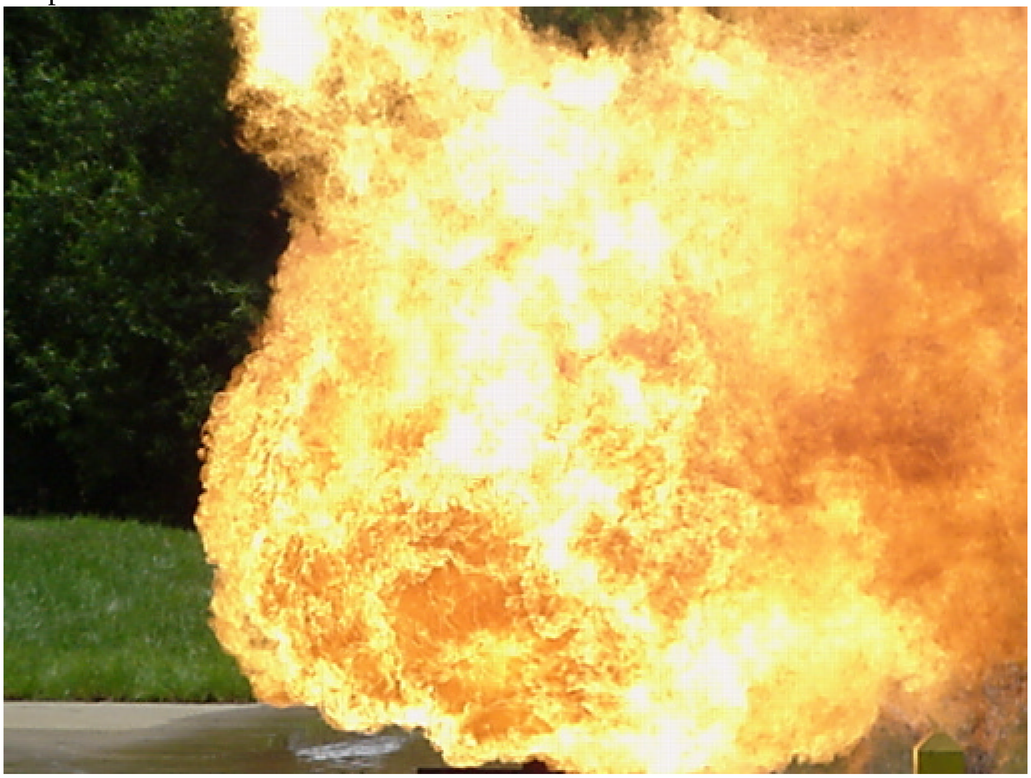
Before propane fires – spray practice:

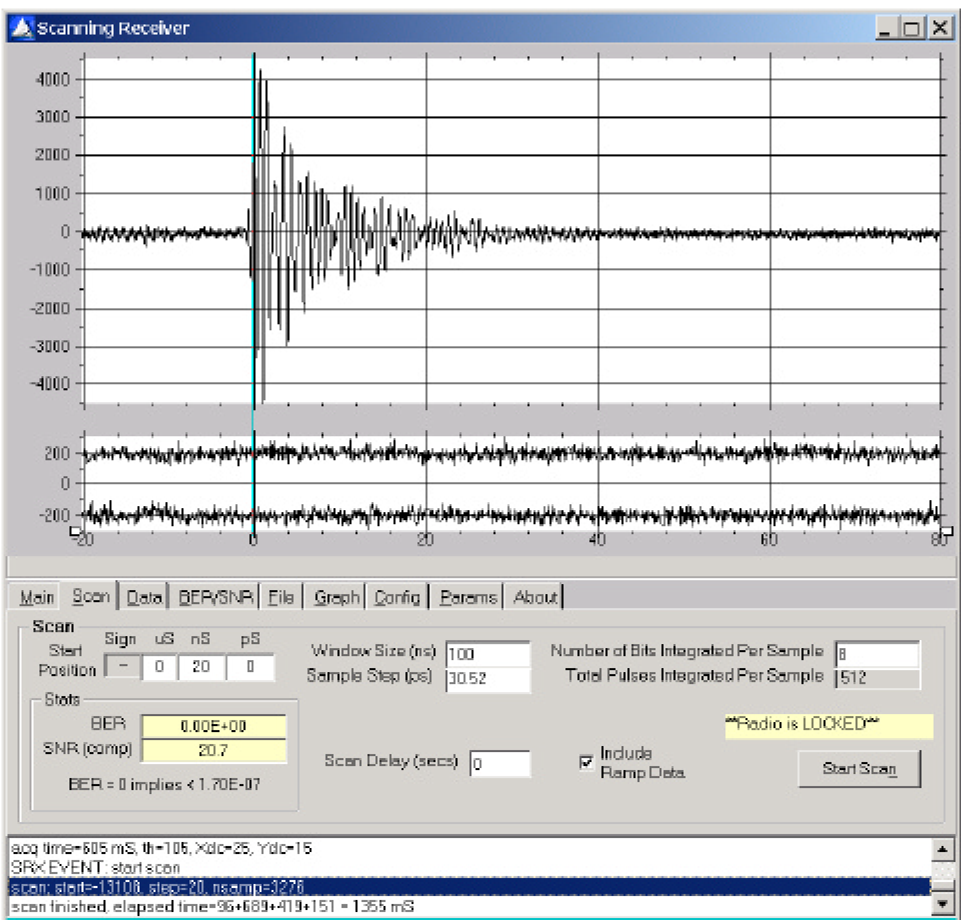


Propane fire 1:

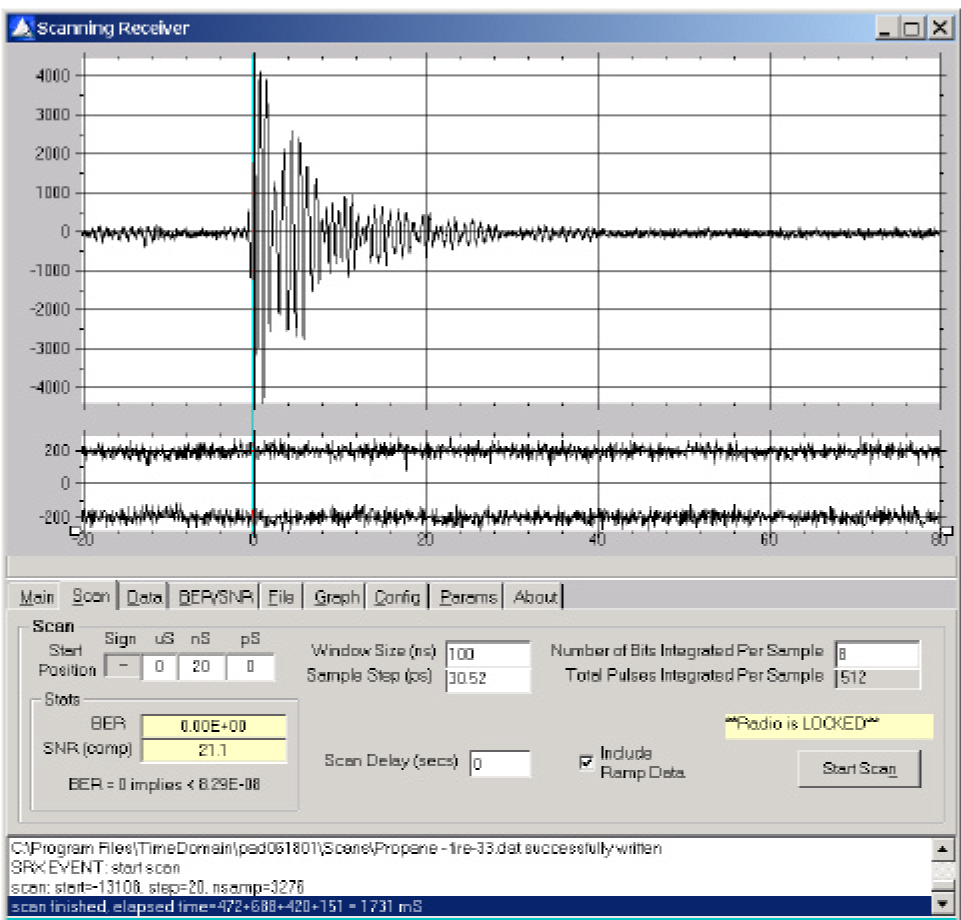


Propane fire 2:

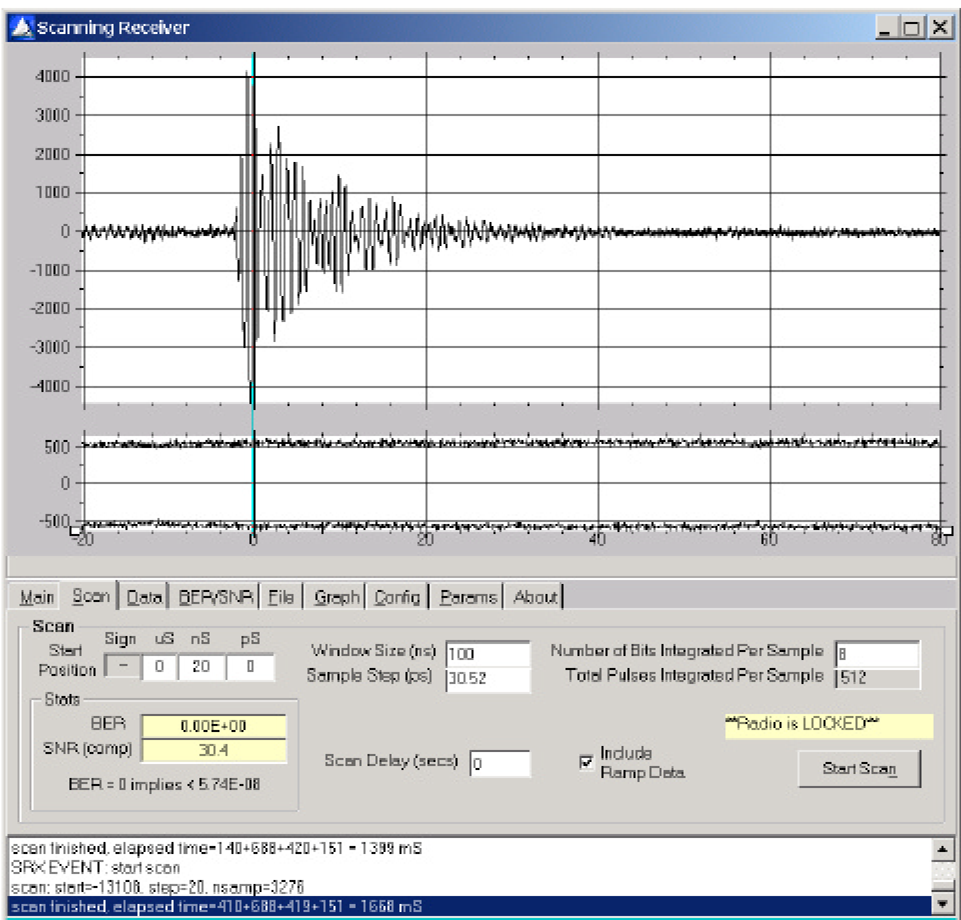




Propane fire 3:



Propane fire 4:



This appendix contains excerpts from the Reduced Ship's Crew by Virtual Presence System released by NSWC Carderock, Code 9534.

AN EMPIRICAL STUDY OF RADIO PROPAGATION ABOARD NAVAL VESSELS

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Cambridge, MA 02139

Abstract - Most existing studies of indoor radio wave propagation have addressed operation in common commercial environments such as warehouses, office buildings and factories. These studies show typical path loss gradients ranging from 3-5, and rms delay spreads ranging from 10-40 nanoseconds. This paper reports the results of research conducted to characterize microwave radio propagation aboard navy ships. Because of its principally steel construction, the ship environment displays significantly different characteristics from commercial environments. In particular, rms delay spreads ranging between 70 and 90 nanoseconds are common. Likewise, path loss gradients are observed to range from slightly greater than inverse square to smaller than unity. These effects of path loss and delay spread and found to be independent of frequency, over the range from 800 MHz to 2.6 GHz.

I. INTRODUCTION

A substantial fraction of the operating cost of any naval vessel is directly proportional to the total staff size. Recent manpower assessment studies have concluded that it is possible to reduce nominal staffing requirements, while at the same time maintain situation awareness and response capability, through the judicious deployment of an advanced monitoring system. Since the bulk of the fleet will consist of existing assets long into the foreseeable future, an important attribute of the monitoring system is the ease with which it may be retrofit. For this reason, all leading candidate system architectures are based upon large embedded networks of wireless self-powered environment sensors.

As with most portable wireless devices, the power consumed by an environment sensor is chiefly determined by the transceiver signal processing necessary to deliver the required quality of service (QoS). For example, to serve an application that requires high net throughput while operating in an environment characterized by a long average delay spread, the system architecture must include some form of adaptive equalization to compensate for the inevitable intersymbol interference [5]. Because of this relation between QoS and power consumption, design of the most energy-efficient, and hence longest life, sensor requires a detailed knowledge of the propagation environment [1].

This paper describes the results of several research activities funded by Mr. Jim Gagorik (Office of Naval Research Code 334) under the Reduced Ships crew by Virtual Presence (RSVP) Advanced Technology Demonstration program as well as a Draper Laboratory funded FY98 IR&D project. The research activities that have been conducted in order to better understand the various aspects of radio propagation aboard naval ships. Section (II) details some of the experimental work performed. Section (III) offers an analysis of the results, and their implications from a system design perspective.

II. EXPERIMENTS CONDUCTED

Gonzalez Testing The first of three studies was performed aboard the destroyer USS Gonzalez, while being serviced at Norfolk Naval Shipyard during the summer of 1998 [6]. This study addressed the issues of radio transmission and radiated interference as observed in several large compartments. Transmission measurements were conducted using a vector network analyzer as described in [3]. Data was collected by sweeping the instrument over frequencies ranging from 800 MHz to 2600 MHz. To provide acceptable time resolution while accommodating large delay spreads, the total sweep range was divided in 9 segments, each of width 200 MHz. The antennas used in this study were of a discone design, to allow a single element to service the entire frequency range. All measurements were conducted at a vertical polarization. At each location where data was acquired, the precise spacing between the transmit and receive elements was recorded, to allow study of the correlation between distance and attenuation. Priori to the first measurement, a through calibration was conducted. All subsequent measurements were referenced to the base of the antennas.

Interference measurements were performed using a portable spectrum analyzer, together with a discone antenna, and a low-noise RF preamplifier. In this configuration, the cascade noise figure as measured at the base of the antenna is 6.0 dB. Data was collected using a 300 kHz predetection bandwidth, and operating the instrument in time-sweep mode, while the measurement frequency was adjusted between 800 MHz and 2600 MHz, in 1 MHz steps. This manner of data collection enables post-processing to estimate the interference statistics, and the rapid identification of pulsed or line-synchronous sources.

Interference and transmission measurements were conducted in three spaces:

- Auxiliary Machine Room One, of dimensions 47'x35'x16', and containing several large rotating machines and equipment consoles.
- Engine Room Two, of dimensions 60'x46'x30', and containing two turbines, many rotating machines, a small workshop and operator stations.
- Main Starboard Hallway, of approximate dimensions 5'x8'x200'.

Several dozen data sets were acquired in each compartment.

Shadwell Testing A study reported by the Naval Research Laboratory indicated the possibility of additional propagation effects induced by the onset and suppression of a fire [7]. In order to further address this issue, researchers from the Naval Postgraduate School (NPS) conducted a set of rigorous instrumented tests aboard the Ex-USS Shadwell, which is permanently-stationed near Mobile, Alabama [2]. The Shadwell is a sophisticated fire research and training facility, maintained by the Naval Research Laboratory. The main testing compartment of the ship provides a fuel pan in which very large fires may be safely maintained, a suppression system based upon the water mist technique, and a ventilation system which allows the thermal and chemical byproducts of a fire to be rapidly expelled.

The test configuration developed and deployed by NPS consisted of high and low gain antenna elements placed diagonally across the fire pan. Transmission data was collected using a scalar network analyzer swept across the 2.4 GHz band. The test set continuously acquired and stored data, allowing for the easy identification and tracking of changes which occur during the various stages of a fire. The test set was also outfit with numerous logging temperature sensors which provided a thermal and spatial profile of the combustion environment.

Each fire event consisted of four distinct sequential stages, characterized as:

- Reference, or Calibration, several minutes.
- Fire Active, 2-5 minutes.
- Suppression (water mist), up to 2 minutes.
- Ventilation and Cool Down, 2-5 minutes.

Numerous events were conducted, fueled by either heptane or diesel.

Normandy Testing Two sets of tests were conducted aboard the USS Normandy (CG-60), a guided missile cruiser. The purpose of the first set was to augment the earlier interference testing performed aboard Gonzalez, by characterizing the electromagnetic interference environment aboard a warship with all systems operating. Testing was conducted during an at-sea exercise in the spring of 1999 off of Norfolk, Virginia. Spectrum analyzer measurements were made over a frequency range of 1 MHz to 3 GHz using a set of four antennas [9].

The second set of tests was conducted at dockside at Naval Station Norfolk during the winter of 2000 when the Normandy was standing down for the Holiday Season. The tests were conducted to evaluate the bit error rate (BER) performance of breadboard 2.4 GHz radios developed at Draper Laboratory, and to further characterize the radio channel in the 2.4 GHz region aboard ship [8].

1.1 III. ANALYSIS OF RESULTS

A typical measured frequency response, acquired on the top floor of a machinery space, is presented in Fig. (1). The figure displays the typical scalloped behavior, wherein arrivals emanating from multiple directions tend to add destructively at the receiver. This same effect is witnessed in all measurements made aboard the Normandy and Gonzalez, as well as Shadwell measurements conducted with low-gain antennas.

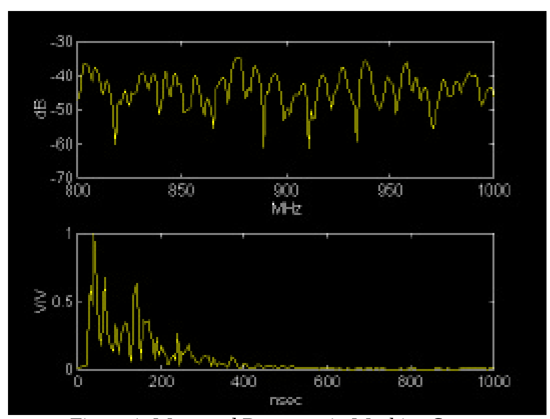

Figure 1: Measured Response in Machine Space

Shadwell measurements made with high-gain elements display almost no scalloping, since the angular selectivity tends to reject arrivals other than the direct line-of-sight. The lower portion of the figure shows an estimate of the channel impulse response, developed using the inverse Fourier technique [3].

Delay Spread An important property to consider, especially for transmission of high-speed data is the rms delay spread, which roughly corresponds to the effective length of the impulse response. The significance of the delay spread is that if comparable in duration to the signaling period, it causes leakage between adjacent symbols, resulting in very high error rates. Estimates of the delay spread were calculated from all measurements, and found to range from below 70 to well in excess of 90 nanoseconds. Using the standard rule-of-thumb, the shipboard channel should support raw symbol rates on the order of 1-2 MSPS without the use of adaptive signal processing. An interesting feature of data collected aboard the Gonzalez is that the mean and standard deviation of the delay spread data display very little dependence upon frequency, as the carrier is swept from 800 MHz to 2600 MHz. The statistics of the delay spread are summarized in Table (1).

Distance Relationships Figure (2) depicts a 900 MHz data set collected aboard the Gonzalez, as a function of the logarithm of interantenna distance. The figure also shows a least-squares fit to the data, which is of the form:

$$T_{dB} = A_{dB} + B\log_{10} d_{meters}. \qquad (1)$$

A represents the one-meter transmission, in dB, and is related to the antenna gain and frequency using the Friis equation [3], [4]. *B* represents the distance-power gradient in dB per logarithm of distance. Data collected aboard the Gonzalez shows that for a given environment, *B* is nearly independent of operating frequency. However, *B* varies dramatically among dissimilar environments, as summarized by Table (1). Values of *B* near inverse-square (20) are indicated for same-floor propagation in large spaces. For propagation between floors, very little dependence on *B* is witnessed. The hallways display a strong guiding effect, in that *B* is -2.87 dB/log(m). This same behavior was witnessed aboard the Normandy, and shown to correlate strongly with radio performance.

Envelope Statistics The fluctuation in received signal strength was investigated by normalizing each frequency response using the corresponding form of Eq. (1), and calculating the sample statistics. The result of this computation for an auxiliary machine space is depicted in Fig. (3), together with a Rayleigh pdf. All measurements, except those conducted with high-gain elements display similar behavior.

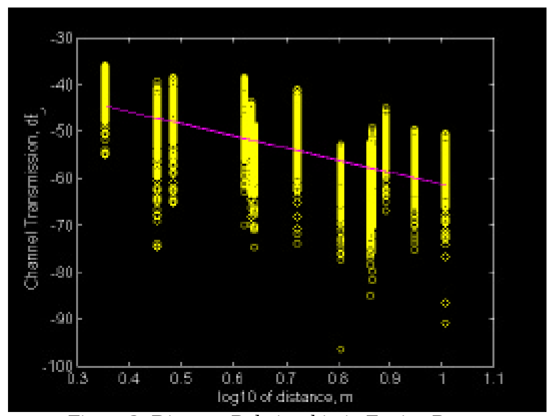

Figure 2: Distance Relationship in Engine Room

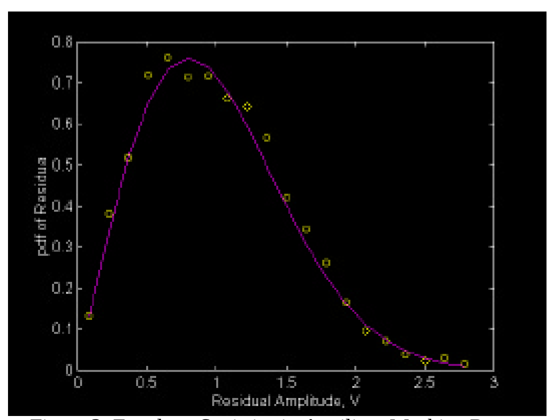

Figure 3: Envelope Statistics in Auxiliary Machine Room

Interference Figure (4) depicts a measured interference profile from the Gonzalez data, over the range of 800 MHz to 1 GHz. In the figure the blue line represents the sensitivity of the measurement system, the purple trace represents the worst-case values over each time sweep, and the yellow curve represents the average value over a time sweep. The discrete sources depicted in the figure are due to commercial wireless services based in the Norfolk area. The frequency region above 1 GHz displayed little activity relative to the noise floor. Aboard the Normandy, the band below 1 GHz was found to be very active with many types of sources. Several signals between 1 GHz and 2 GHz were also noted, but the band from 2 GHz to 3 GHz was found to be nearly interference-free.

Effects of Fire Measurements made aboard the Shadwell show an increase in attenuation of roughly 0.5 dB during the active phase of the fire. Since this increase appears gradually, and in virtual lockstep with changes in ambient temperature, it is probably due to heating of the test instrumentation. The attenuation displays an abrupt increase of about 0.7 dB with the actuation of the fire suppression system. This attenuation diminishes as the ventilation system evacuates steam from the test environment[2].

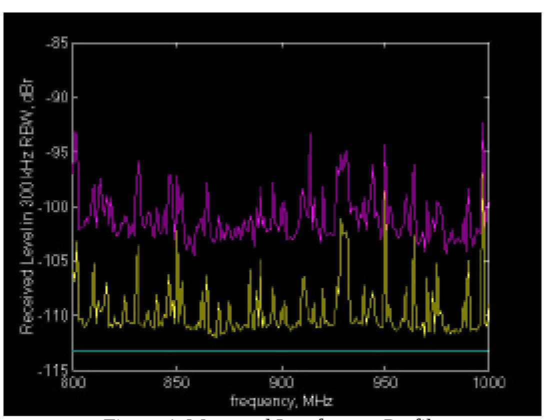

Figure 4: Measured Interference Profile

Space	? ?$_r$ ms	? ?$_r$ ms	A_{900}	A_{2500}	B
AUX TOP	85.9 nsec	7.56 nsec	-26.6	-36.4	-24.7
AUX TB	80.5 nsec	3.4 nsec	-43.5	-55.9	-6.97
ER2 TOP	83.0 nsec	15.1 nsec	-31.1	-41.4	-21.8
ER2 TB	83.8 nsec	3.87 nsec	-48.9	-55.4	-8.90
Hall	72.2 nsec	3.49 nsec	-42.1	-51.9	-2.87

Table 1: Summary of Propagation Parameters

IV. CONCLUSIONS

As compared with typical commercial environments, radio propagation aboard naval vessels displays both much longer delay spreads and much milder path loss gradients. These traits tend to favor low-power, medium-bandwidth applications, which, due to the environment properties, achieve respectable coverage with low transmitter power. While significant interference is present at frequencies below 1 GHz, especially when in port, very little interference is witnessed for frequencies above 1 GHz. Both a fire and its suppression are seen to have minimal direct impact on radio propagation. The secondary aspects of a fire, such as thermal and water damage are expected to be far more important.

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Reliability and Survivability in the Reduced Ship's Crew by Virtual Presence System

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schwartz@draper.com

ABSTRACT

The Reduced Ship's Crew by Virtual Presence Advanced Technology Demonstration was a 3-year program (1999-2001) to show the feasibility of employing wireless sensors on naval ships. Environmental, structural, personnel, and machinery sensors were demonstrated.

This paper describes the RSVP architecture, highlighting the aspects of the architecture that contribute to the system's reliability and survivability. It also describes the demonstrations that were performed and their results.

Keywords — **Wireless network, survivable network, monitoring system, distributed system**

TABLE OF CONTENTS

a. INTRODUCTION

Navies throughout the world are seeking to build ships that will be less costly to build, maintain, and operate than at present. The role of electronics, and in particular dependable electronics, in achieving these goals cannot be overstated. Reductions in crew size will contribute to lower operating cost, but the loss of information from dozens to hundreds of sophisticated sensors – people – no longer on a given ship must be addressed. On the assumption that the solution will come from large numbers of networked sensors and computers employing technologies that are currently emerging, the Office of Naval Research commissioned the Reduced Ship's Crew by Virtual Presence (RSVP) Advanced Technology Demonstration (ATD) [1,2,3] to develop a proof-of-concept system.

The ATD was based on a number of presumptions: The employment of wireless technology will result in reductions in the cost of installing and maintaining the sensors. To minimize the impact on maintenance cost, the sensor system must be reliable. Reliability, along with stability and low power utilization, will come from the use of microelectromechanical system (MEMS) sensors. Eliminating wiring while not relying on batteries and the attendant maintenance burden implies the need for alternative power sources, such as energy harvesting devices. Since the sensor system will be installed on a warship where it will contribute to the ship's survivability, it must have high availability and must be survivable itself.

The goal of the RSVP ATD was to show the feasibility of a system embodying these features. The focus was a single compartment, although in an operational installation most if not all the compartments on a ship would be instrumented.

Sensors were demonstrated in four functional areas. Environmental sensors monitored ambient environmental conditions and damage-related phenomena. Structural sensors monitored the condition of the ship's hull. Personnel sensors monitored physiological conditions and provided inputs that allowed individuals to be tracked as they moved from compartment to compartment. Machinery sensors monitored a number of conditions on a ship's service gas turbine generator and on a fire pump.

The culmination of the ATD was a series of demonstrations, summarized in Table 1.

b. SYSTEM ARCHITECTURE

1.1.1 2.1. System components

The RSVP system architecture is shown in Figure 1. The architecture is composed of the following elements.

- Sensor units
- Access Points (AP)
- System Health Monitor (SHM)
- Ship's local area network
- Watchstation

There is a sensor unit corresponding to each of the four functional areas.

Environmental Sensor Clusters are mounted on convenient structures to monitor the ship's internal environment. They consist of internal sensors, a low-power processor, a low-power radio, and a wireless power source. Internal sensors monitor temperature, smoke, ionization, humidity, air pressure, flooding (via a differential pressure sensor connected to an external pipette), oxygen, and carbon monoxide levels, and acoustic transients. An external interface can be used to monitor hatch closure. ESCs communicate wirelessly with APs, employing low-power radio transmissions.

Table 1. RSVP Demonstrations

Time Period	Location	Space(s) Instrumented	Nature of Demonstration
January 2001	Land-Based Engineering Site, Naval Surface Warfare Center, Philadelphia	Reconstruction of an Arleigh Burke-class destroyer propulsion plant	Functionality under realistic conditions, including actual machinery and simulated failures
March – May 2001	USS Monterey (CG-61), pier-side and at sea	Main Engine Room 2	Functionality under operational conditions
Septem-ber 2001	Ex-USS Shadwell (LSD-15), Mobile, Alabama	Various compartments and passageways	Functionality during damage-control conditions
February 2002			

Structural Sensor Clusters are mounted on beams and the hull to monitor parameters related to the ship's structural condition. SSCs consist of internal sensors, a low-power processor, a low-power radio, and a wireless power source. Using external interfaces to instruments mounted directly on beams and the hull, SSCs monitor strain on the structural members, seaway acceleration, and shock. The only internal sensor employed by an SSC monitors temperature. SSCs communicate wirelessly with APs, employing low-power radio transmissions.

Intelligent Component Health Monitors obtain data from transducers mounted on a machine. The data items vary from machine to machine, and include parameters such as temperature, acceleration, and electrical measurements. ICHMs and System Health Monitors are powered by ship's power but communicate wirelessly. ICHMs communicate with SHMs, and SHMs in turn communicate with Access Points, with IEEE 802.11 being employed in both cases. While this communication chain would appear to have one extra link – indeed, the SHM functionality could have been implemented in the APs – the thought is that in the future machines will have the equivalent of ICHMs and SHMs installed by the manufacturer. In that case, the SHM would manage data internal to the machine's electronics and would communicate with the rest of the ship via Access Points.

Personnel Status Monitors are devices worn by individuals. They sense parameters related to the wearer's well being and provide the means for the wearer to be located on the ship using an algorithm based on signal strength. PSMs consist of sensors, low-power processors, low-power radios, and batteries. PSMs monitor the individuals' heartbeat, axillary temperature, spatial orientation, and acceleration. They have an "emergency" button and can be in an online or offline mode; the latter is overridden if the PSM receives a message that the ship has gone to General Quarters. The PSM transmits vital signs once per minute, and transmits a message to aid the locating algorithm every 15 seconds when the wearer is stationary or moving slowly, and every second when the wearer is moving quickly. The one-second transmissions allow a wearer to be tracked while running down a passageway.

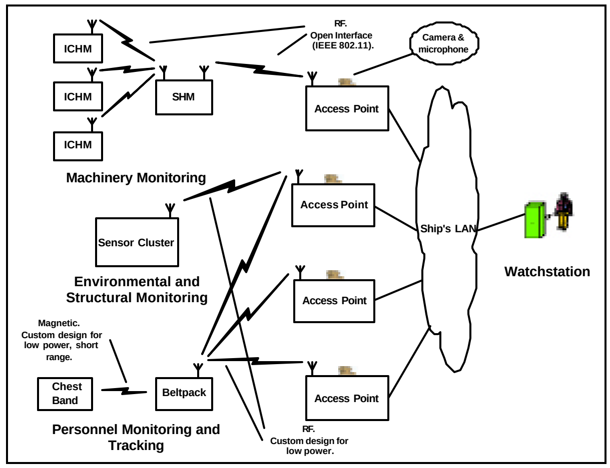

Figure 1. RSVP System Architecture

Other classes of sensor units, such as sensors incorporated in ordnance and materiel and personal digital assistants, could easily be accommodated by RSVP.

Access Points are the interface between the sensor units and the ship's backbone LAN. APs communicate with sensor units and SHMs wirelessly, and with Watchstations and other APs via the LAN. APs exchange data with other APs in the same compartment so that each has a complete version of all the data in that compartment. APs employ data fusion algorithms to determine whether alert or alarm conditions exist, and to suppress false alarms. For example, an alert exists if a single SC detects an abnormal condition, while an alarm is generated if multiple SCs concur that an abnormal condition exists; in the case of fire detection, multiple sensors in a single ESC must concur for there to be an alert. One AP in a compartment is responsible for transmitting appropriate data and information to the Watchstation.

Each Access Point incorporates a camera and microphone. Audio and video are compressed and stored in a loop recorder implemented with hard-drive memory.

It was assumed that warships of the future would have a reliable, survivable LAN installed as part of its infrastructure. Also assumed was that the LAN would be implemented with a switched network technology, which allows paths to be reconfigured around failed or damaged components.

The RSVP demonstrations employed a Watchstation dedicated to RSVP, but in an operationally deployed system the Watchstation functions would be integrated into the ship's general-purpose Watchstations. Watchstations are the interface with the ship's operators, presenting information on a display terminal and taking commands via user input devices such as keyboard and trackball. The operator can request alarm information or specific data from a compartment, as well as live or "instant replay" video and audio from any Access Point.

Sensor Clusters are intended to operate between five and ten years without maintenance. To accomplish this, Sensor Clusters were designed to be powered by energy-harvesting technologies – devices that generate electricity from heat, light, or vibration – backed up by batteries. The use of these low-capacity power sources dictates a design that minimizes power usage. Sensor Clusters operate by periodically (1 Hz) powering up from sleep, applying power to transducers, sampling the transducers, making a decision as to whether there is a need to uplink data, powering up the transmitter and transmitting a data frame if appropriate, and returning to sleep. Whether the Sensor Cluster decides to transmit or not depends on whether the data is judged to be "interesting." Typically the Sensor Cluster transmits at a 0.1 Hz rate to conserve power, but if the data suddenly becomes interesting it will transmit at a 1-Hz rate. (It is preferable to run the battery down than to lose the ship.) At a lower frequency (0.01 Hz), the Sensor Clusters enable their receivers, resync, determine whether they are required to receive downlink, and if so receive and process a downlink frame. This scheme results in Sensor Clusters spending 97% of the time in the sleep mode, with just a timer running to generate the next wake up, 99.8% of the time with the radio transmitter being off, and 99.99% of the time with the radio receiver being off. To achieve this, it was necessary to design a radio that not only made efficient use of power when on, but also that could be brought from dormancy to operation in milliseconds. It was also necessary to choose transducers that could be sampled with minimal warm-up periods.

The use of MEMS-based transducers provides benefits of small power consumption, high reliability, and high stability, all of which contribute to low-maintenance operation. MEMS sensors were used where readily available: for temperature, humidity, pressure, differential pressure, acceleration, and strain. Conventional sensors were used where MEMS devices were unavailable: for oxygen, carbon monoxide, photoelectric, and ionization. The non-MEMS sensors were the limiting factors in determining SC volume and power utilization.

1.2 2.2. Radio-frequency communication

RSVP radios operate in the 2.4-GHz industrial, scientific, and medical band, which allows unlicensed operation and the use of readily available components and small antennas, namely. Several distinct protocols are employed, due to differences in characteristics of the devices involved and the nature of the messages.

The choice of communication scheme at each interface is influenced by the power requirements of the units at each end, which are summarized in Table 2. Other considerations that dictate the choice of communication are the required data rate and whether a connection-oriented or connectionless interface is appropriate. Data transfers between SCs and APs lend themselves to connection-oriented communication, because a service level can be guaranteed during a damage event, when a large number of Sensor Clusters transmit at the highest rate. Data transfers between PSMs and APs are naturally connectionless, because it would degrade responsiveness to continually establish and break down connections as the wearer moves about the ship. The upshot is that three different protocols are employed within the 2.4-GHz band, as summarized in Table 3.

For communication between Sensor Clusters and Access Points and between PSMs and APs, the band has been divided into 142 continuous-wave channels. Two of these channels are operated with an Aloha media-access method without acknowledge. These same two channels, one a primary and the other a backup, are used throughout the ship.

Using Aloha, a sender transmits asynchronously without first monitoring the channel to determine whether it is in use. This results in a low-power, connectionless means of communicating. However, a percentage of messages will be lost due to senders transmitting concurrently.

The RSVP implementation of Aloha is unconventional in that there are no acknowledgements or retransmissions. Acknowledgements were avoided to minimize power consumption. A sender will soon send another message with similar content, and no one data sample is so important that it cannot be lost.

The Aloha channels are used by PSMs to uplink data, and are the means by which a Sensor Cluster finds out which channels are being used for SC uplink by nearby Access Points.

The remaining 140 channels are used for uplink from and downlink to Sensor Clusters. These channels are operated in a time-division multiplex fashion, with each AP having exclusive use of a single channel for both uplink and downlink. Frequency reuse is employed where compartments are far enough away that there will be no interference. On each channel, Sensor Clusters are assigned a particular time slot in a repeating frame (1 Hz) by the channel's AP, and thereafter have the option of transmitting or not transmitting during that reserved time slot. This scheme allows a Sensor Cluster to transmit messages at 1 Hz when it judges its data to be interesting, and at a lower rate, 0.1 Hz or less, when there is nothing to report.

Table 2. Power Considerations for Units Performing RF Communication

Unit	Power Consideration	Implication
Sensor Cluster	Severe. Intent is to run on harvested energy for years, backed up by batteries.	Minimize number of transmissions. Minimize opportunities for receptions. Minimize warm-up period. COTS solution not available.
Personnel Status Monitor	Moderate. Individual responsible for replacing or recharging battery, as with a pager.	Same as Sensor Cluster. Battery maintenance is a burden on wearer, and should be minimized.
Access Point	None. Connection to ship's power assumed.	For comm with SCs and PSMs, perform high-power operations such as receiving. For comm with other devices powered by ship's power, power efficiency not a constraint, so COTS solution may be employed.
Intelligent Component Health Monitors	None. Connection to machinery or ship's power assumed. Wireless applies only to communication.	Power efficiency not a constraint, so COTS solution may be employed.
System Health Monitor	None. Connection to machinery or ship's power assumed. Wireless applies only to communication.	Power efficiency not a constraint, so COTS solution may be employed.

Communication between SHM and AP is carried out using commercial radios operating under the IEEE 802.11 standard. Commercially available 802.11 AP software to perform network management is installed in every AP of the compartments that contain machinery. An SHM communicates with a single AP in the compartment. If that AP fails, another AP in the compartment takes over the communication function.

Communication between ICHM and SHM is also carried out using commercial radios operating under the IEEE 802.11 standard. ICHM/SHM and SHM/AP communication employ different spreading strategies, which allows both to use 802.11 without interfering with each other.

1.3 2.3. Wired-network communication

RSVP communication over the ship's LAN is performed using the publish/subscribe paradigm. Individual Access Points receive directly a subset of the sensor data corresponding to the subset of Sensor Clusters with which it communicates. An Access Point obtains the data that had been received directly by the other APs in its compartment by subscribing to that data.

Table 3. RF Communication Requirements

Units *Functionality*	**Data Rate**	**Connection**	**Solution**
AP → SC *SC acquire frequencies used in compartment*	Low	Connectionless	Random access (Aloha without acknowledge)
AP ↔ SC *Data uplink, downlink*	Low	Connection oriented	Time-division multiplex (each SC has a reserved slot in repeating frame)
AP ↔ PSM *Data uplink, downlink*	Low	Connectionless	Random access (Aloha without acknowledge)
AP ↔ SHM *Data uplink, downlink*	Med	Connectionless	IEEE 802.11
SHM ↔ ICHM *Data uplink, downlink*	Med	Connectionless	IEEE 802.11

A Watchstation obtains the data it needs by subscribing to that data. This data is a function of the active displays on the Watchstation. At the highest level, the Watchstation subscribes to alarms and has nothing to do until an alarm is generated. When an alarm is generated, there is a need at the Watchstation to display information about that alarm and to display information related to dealing with the alarm. The pertinent information is obtained by subscribing to it.

When a Watchstation subscribes to data in a compartment, any Access Point in the compartment has the capability to publish it. The APs designate one member of their group, the "prime," to do the publishing. If the "prime" fails, one of the other APs in the compartment takes over this function.

A Watchstation obtains video by subscribing to it. The AP connected to the requested camera is the publisher, regardless of whether that AP is "prime" for data publications.

1.3.1 2.4. Redundancy, fault tolerance, and survivability

The RSVP concept employs more than the minimal set of Sensor Clusters and Access Points needed to meet the sensor monitoring requirements. This accomplishes three objectives:

- Spatial diversity of transducers with increased data sources for data fusion algorithms. This results in a lower number of false alarms and missed detections.
- Graceful degradation following failures. There is no repair or replacement of failed units unless a particular compartment had suffered a disproportionate number of failures.
- High degree of survivability. A single AP can communicate with 100 SCs and 100 PSMs. This allows the system to continue functioning with a single surviving AP in a compartment. Operation continues even if all APs in a space are damaged or compartment boundaries are destroyed.

For the most part, Sensor Clusters are not internally redundant because it is necessary to install redundant units for survivability. Two particular sensors were replicated in the ESCs.

- Thermistor: One thermistor was triplicated to demonstrate the use of redundancy to improve the fidelity of the data. Logic onboard the Sensor Cluster performs a selection algorithm and provides a single temperature value, either the middle value or the mean of the two values closest together.
- Oxygen sensor: The oxygen sensor has a limited lifetime owing to its implementation as an electric generator powered by an oxidation reaction. To extend the lifetime of the ESC, multiple oxygen sensors are employed sequentially. When the active oxygen sensor is depleted, the ESC switches to the next in line.

Table 4 gives the responsibilities for fault detection, identification, and repair (FDIR) in the RSVP system. Each row in the table gives the activities performed by an SC and AP as a consequence of a particular failure. Taking the first row of the table as an example, a passively failed Sensor Cluster is not detected by any SC. The AP detects that the SC has failed by noticing the absence of its data. Isolation is trivial, because only one SC is assigned to use that slot in the repeating frame. The AP ceases to use data from the failed SC, and eventually frees up its slot to be assigned to another Sensor Cluster.

Even though zero maintenance is the ideal, it is inevitable that some spaces would suffer more failures or damage than others. A space that no longer had enough operating equipment would degrade system availability, which would degrade the ship's ability to accomplish its mission. Therefore a study was performed [4] to determine the impact on availability and operating cost of various options, including repair strategies. Three repair strategies were compared, all assuming a mission time of 50,000 hours (5.7 years):

- Repair components as they fail
- Perform no repair until the amount of functioning equipment in a space is inadequate, then repair just enough components to make the

space available again

- Perform no repair until the amount of functioning equipment in a space is inadequate, then repair all failed components in that one space

All three repair strategies allowed the ship to meet an 0.95 availability standard. The strategy of repairing just enough to make the space available again provided the lowest overall cost.

Table 4. FDIR in RSVP

Failure	Sensor Cluster FDIR	Access Point FDIR
SC (passive)	None	Detect absence of data; data from absent SC is not used in computations. SC's assigned slot may be assigned to another SC.
AP (passive)	If linked to failed AP: detect absence of downlink; establish communication with another AP	Detect absence of wired-network messages from failed AP; if that AP was prime, another becomes prime. If the failed AP had been communicating with an SHM, another AP takes over that communication
SC or AP radio (babbles on a channel or channels, making it or them unusable)	If employing affected channel: detect absence of downlink; establish communication with another AP	AP using affected channel: detects absence of data from SCs, but take no automatic action. AP can be reprogrammed to use different channel
Ship's LAN	None	Detect failed transmissions to other APs. Establish path through network that avoids failed or damaged parts.
Watchstation	None	None. Crew will switch to another Watchstation, which will subscribe to the data it needs.

The desire for data to be survivable militated against the use of Aloha for data transmissions between SCs and APs. When multiple Sensor Clusters transmit at the highest rate, such as in a fire situation, there would be many collisions between packets transmitted by different SCs, and therefore much loss of data. Aloha is acceptable for communication with PSMs because the situation in which PSM data is most important is when there are few PSM wearers in a particular space.

While beyond the scope of RSVP, an operational system would use encryption in the RF links. An enemy should be denied the ability to introduce easily spurious data that would result in a flood of false alarms.

A need to protect against jamming was not identified. An enemy who is capable of disabling RSVP by transmitting a radio-frequency beacon would certainly attack the combat system instead.

c. DEMONSTRATIONS

RSVP demonstrated the feasibility of wireless sensing, and of the low-power electronics necessary to enable sensors being powered by harvested energy. Energy-harvesting devices were deployed on the USS Monterey, and were found to be promising but inadequate, due to level of power output, device size, or mounting requirements. The MEMS sensors that were employed behaved as predicted.

Sensor Clusters, Access Points, Intelligent Component Health Monitors, System Health Monitors, and Personnel Status Monitors were all seen to operate correctly in non-failure situations. Individuals wearing PSMs were tracked as they moved from compartment to compartment. Sensor Cluster and Access Point failures were simulated by removing power to an AP or SC, and correct operation was observed. SCs acquired initial sync when powered on and acquired sync with another AP when the first AP failed. APs responded correctly to SC failures, and transferred primacy when the prime AP failed. SHMs switched from communicating with a failed AP to one that was working.

There was no need to induce failures of the ship's LAN and Watchstations. The dependability of the ship's LAN would be well established before being installed as part of a ship's infrastructure. Computers standing in for Watchstations were frequently power cycled in the normal course of events with no adverse effect.

APs performed data fusion and transferred data to the Watchstation as appropriate, as well as live and recorded video and audio when requested.

The Aloha, time-division multiplexing, and IEEE 802.11 RF protocols operated successfully without interfering with each other, even though all operate in the same 2.4 GHz band. This RF traffic did not interfere with RF communication at any of the demo sites, nor was RSVP susceptible to RF interference. A naval communications system was observed to affect the output of the carbon monoxide sensor, necessitating shielding being added to that sensor in every ESC.

d. CONCLUSIONS

RSVP demonstrated that wireless sensing is feasible in the naval environment, and that MEMS sensors can be employed in this capacity. Energy-harvesting devices were shown to be promising, but immature. Progress is needed in several areas for the RSVP approach to be practical.

There is a need for low-power, standards-based radios. Existing standards-based radios consume too much power to be employed in an energy-harvesting situation.

Energy-harvesting devices currently require special installation procedures. To be practical, these devices must be cheap, durable, and capable of being incorporated in a product that has a minimal installation procedure. Failing that, alternative power sources such as fuel cells and ion generators should be pursued.

The lack of availability of MEMS chemical sensors limited the degree to which Sensor Cluster size and power utilization could be minimized. Advances are needed to produce MEMS oxygen, carbon monoxide, carbon dioxide, photoelectric, and ionization sensors.

Table 5. RSVP Features Demonstrated

Feature	LBES	USS Monterey	Ex-USS Shadwell
Wireless sensing	Environmental, structural, and machinery	All functional areas	All functional areas
MEMS sensors	Yes	Yes	Yes
Energy harvesting	No	Thermal, vibrational, and photonic devices	No
Uplink transmission rates vary with interest level	Yes	Yes	Yes
Live and recorded audio and video	Yes	Yes	Yes
AP failure causes SC to migrate to another AP	Yes	Yes	Yes
AP failure causes SHM to migrate to another AP	Yes	Yes	No
Fire detection	Simulated conditions, modified algorithm	Simulated conditions, modified algorithm	Actual fires
Flood detection	Simulated conditions	Simulated conditions	Actual flooding
Personnel Status Monitor tracked as wearer moves	No	Multiple Access Points in a single space	One AP in each of 12 different spaces

REFERENCES

RSVP documents are available at http://rsvp.rk.anteon.com

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[4] Schwartz, G., "RSVP Availability and Cost Modeling," Draper Laboratory memo RSVP-00-009, 27 March 2000.

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2.0 Risk Mitigation

2.1.1 RF Testing

RF Radiated/Susceptibility Tests

A critical part of the RSVP system is the wireless communication network. It must operate reliably in a less than ideal environment inside of ship spaces where there is a lot of machinery and other obstacles disturbing radio wave propagation. In addition, there are many electromagnetic noise and interference sources that could degrade its operation.

The purpose of the shipboard EMI/EMC testing was to determine a typical electromagnetic environment in three different ship spaces in order to find potential interference and noise problems for the RSVP Communication System. These tests were made aboard the USS Normandy (CG-60), a Ticonderoga Class Aegis Cruiser. They were conducted during the period of April 6-8, 1999 off Norfolk, Virginia under conditions where most shipboard systems were operating.

Since the operating frequency band for RSVP is planned to be the 2.4 GHz ISM band, this was of the most interest. Also, since the present RSVP receiver design uses IFs of approximately 100 MHz and 10.7 MHz, the bands surrounding these frequencies were also of critical interest.

The EMI/EMC measurements were made over several bands spanning the range 10 KHz to 3 GHz using a set of antennas and a spectrum analyzer. The entire band was included in order to have a point of reference should interference problems develop in the sensors or in data and signal processing electronics.

The “Shipboard EMI/EMC Test Report ” [ref 8] describes the test methodology, test environment, pertinent measurement data and the conclusions drawn from the at-sea testing. The cooperation and assistance of the officers and enlisted crew of the USS Normandy is gratefully acknowledged and sincerely appreciated.

The EMI/EMC Shipboard Tests on the USS Normandy produced encouraging results. Interfering signals in the desired 2.4 GHz ISM band were found to be non-existent in the ship spaces measured. The propagation tests showed that communication at the desired data rate of 200 kbit/sec can be achieved under near “worst case” conditions providing the receiver’s noise figure is sufficiently low. Under actual operating conditions with several access points, SNR’s should be significantly higher on average.

Breadboard Radio Testing

Radio tests were conducted aboard the USS Normandy (CG-60) at Naval Station Norfolk during the week of 02 January 2000. The purpose of the tests was to verify the performance of the RSVP breadboard radios in a realistic environment and to further determine the radio channel characteristics in Main Engine Room 2 and Auxiliary Machinery Room 1. These spaces present a severe multipath propagation environment due to the presence of many large pieces of machinery that reflect and scatter radio waves.

It is in fact this severe multipath environment that actually enhances the overall performance of the RSVP radio system. By providing a large number of reflected and scattered signals of random phase and amplitude, the shadowing and blockage effects of the machinery are minimized. Reliable links may be established over paths which provide absolutely no direct line-of-sight. This means that the number of Access Points required to communicate with sensor clusters may be kept low, perhaps only two or three even for large spaces like the Main Engine Room. The data taken actually show that a single, carefully placed Access Point Radio could reliably communicate with most any point within the room. System availability requirements would dictate more than one, so a quantity of two or three is probably a more realistic minimum.

The prototype of the low power RSVP radio is shown in Figure 2.

RSVP Radio Breadboard

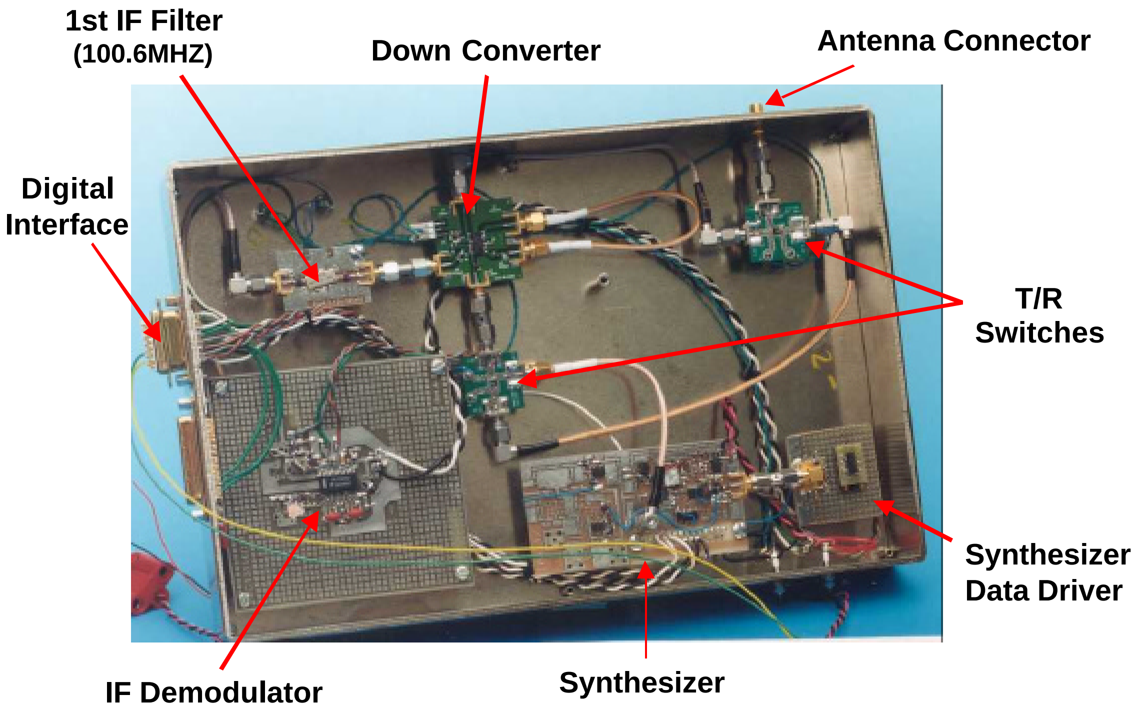

Figure 2 RSVP Radio Breadboard

RF/Fire Testing

The Naval Postgraduate School was tasked to conduct a study on the effects of fire on RF communications. The objective was to quantify experimentally the effects of ship compartment fuel fires (diesel and heptane) and the water mist fire extinguishing system on the propagation of RF signals in the 2.4 GHz to 2.485 GHz ISM frequency range using the ex-USS Shadwell fire research facilities operated by the Naval Research Lab. The test was conducted in May of 1999. RF Attenuation in the ISM band was measured using a pair of narrowband, narrow beam (high gain/directivity) linearly polarized antennas. The effects of fire and water mist fire-extinguishing system were also measured using a pair of non-directional patch antennas which are more representative of typical communications antennas for indoor use. The antennas were positioned in the “simulated” machine space such that the “fire source” was approximately halfway between the transmitting and the receiving antenna. The measurements indicated that the effect of a ship compartment fire and the water mist fire extinguishing can be modeled as rapid, frequency selective fading with relatively small average value of signal loss (the probability of signal gain is slightly smaller than the probability of signal loss). Complete details can be found in the “Effects of Fire and Fire Extinguishing on Wireless Communications in the 2.4 GHZ ISM Band” report [ref 9].

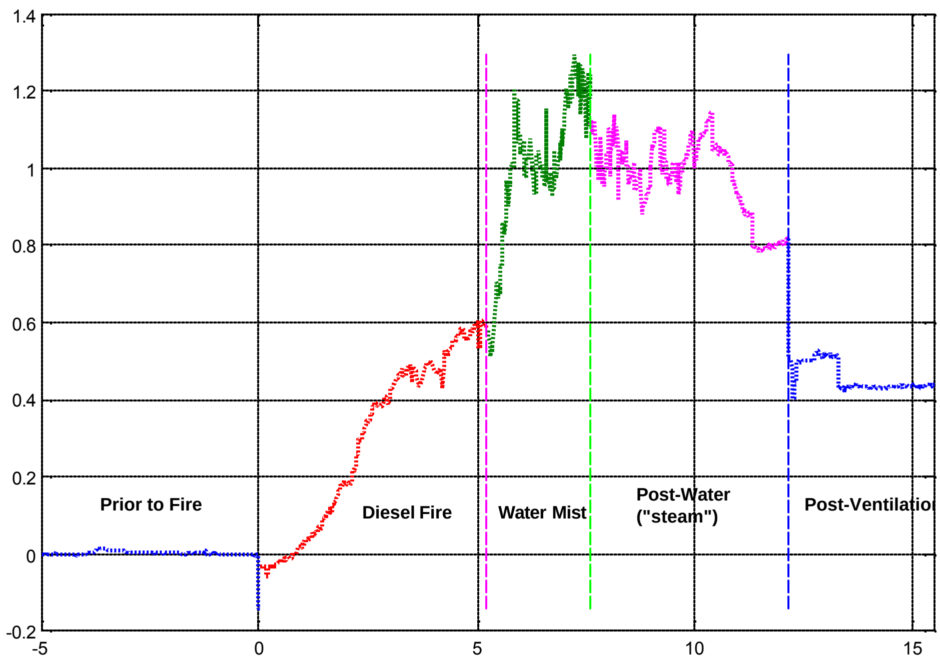

Figure 3 Frequency-Averaged Attenuation for Directional Antennas

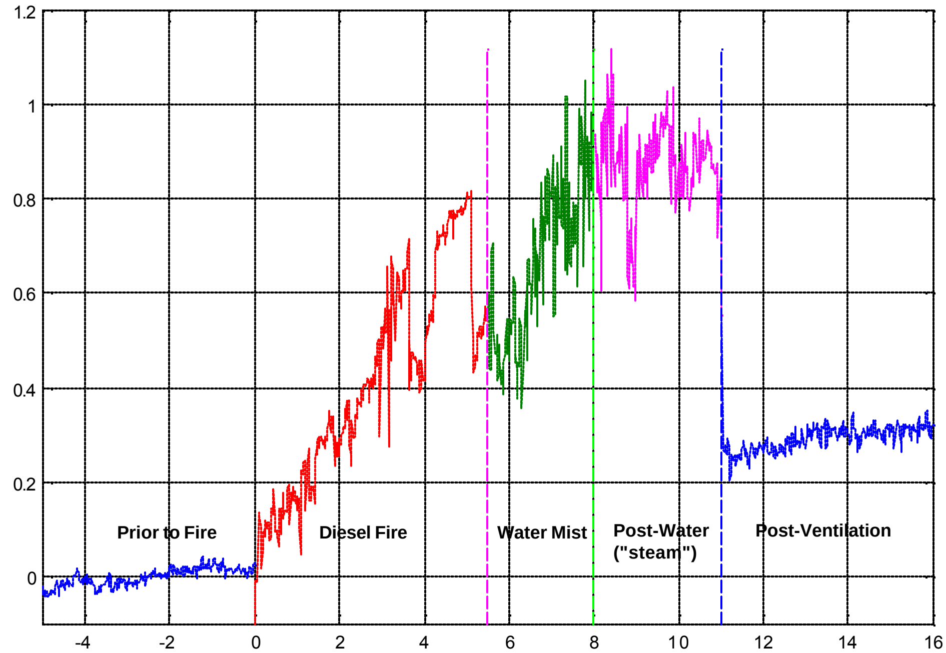

Figure 4 Frequency-Averaged Attenuation for Patch Antennas

The effects of fire and water mist fire extinguishing were found to be profoundly different for directional (high gain) and non-directional (low gain) antennas

The difference is caused by the prevalence of a single, direct path for the directional antennas as opposed to the multipath propagation for the non-directional antennas

The attenuation per unit length for directional antennas exhibits relatively small variations with time and frequency. The attenuation due to water mist extinguishing was substantially larger than the attenuation due to the fire itself.

The average for attenuation for Directional Antennas (includes fire and water mist extinguishing) in the entire 2.4 GHz ISM band was 0.69 dB/m for vertical, and 0.54 dB/m for horizontal, with almost 100% of the values in the 0 to 2 dB/m range.

The loss of only 2db was encouraging, indicating that the RSVP RF transmission would be able to overcome this attenuation. The patch antenna produced similar results.

2.1.2 Data/Information Fusion

Information Architecture

The manner in which RSVP information is distributed throughout given compartment is through a publish/subscribe paradigm. The basic methodology is people or processes subscribe to RSVP information, such as fire alarms. The compartment's APs are the publisher of fire alarm messages. The APs hold on the fire alarm subscription until it cancelled by the subscriber. No further information needs to be sent, once an AP determines an alarm the AP automatically knows who he needs to send it to by virtue of the subscription. This messaging approach minimizes LAN traffic. Figure 5 presents this approach graphically.

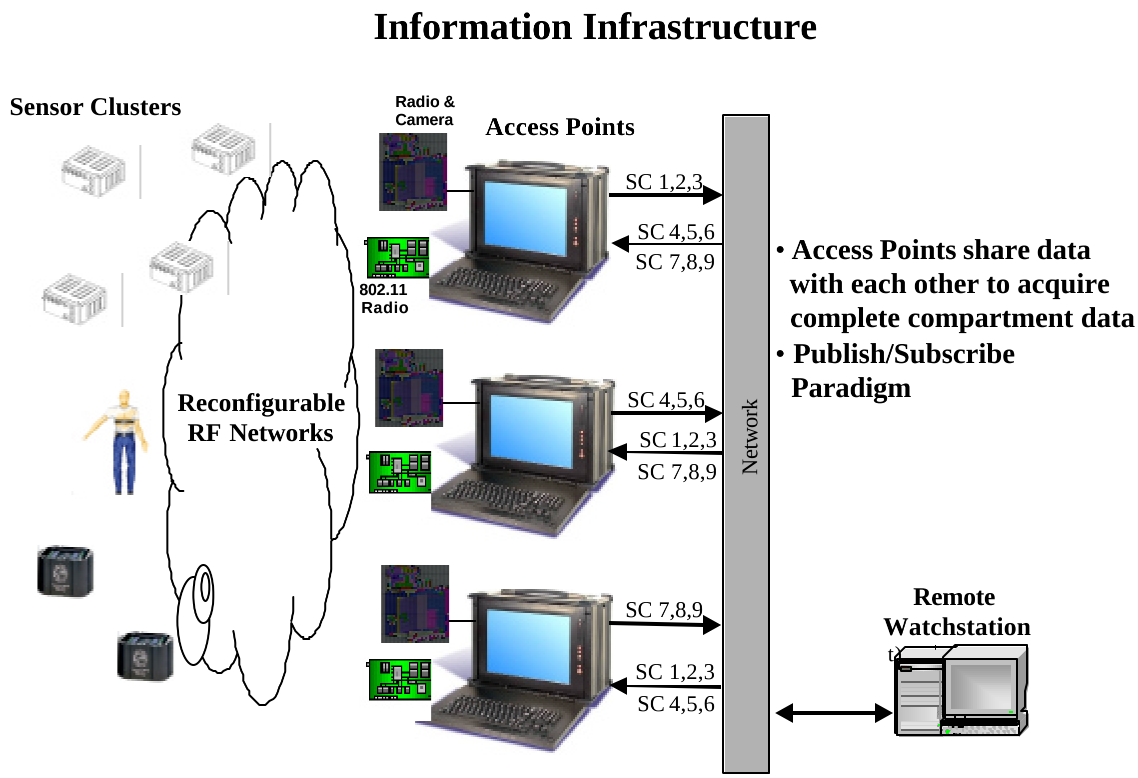

Figure 5 Information Infrastructure

Data Fusion

Understanding the different types of data fusion that are needed in a system like RSVP is very difficult. RSVP is intended to feed data/information to other systems and processes and some of the systems have not been developed yet. Figure 6 is a block diagram that describes the different levels of data fusion within the RSVP architecture. More detailed discussion concerning the data fusion can be found in the RSVP Systems Engineering Study and other related RSVP documents.

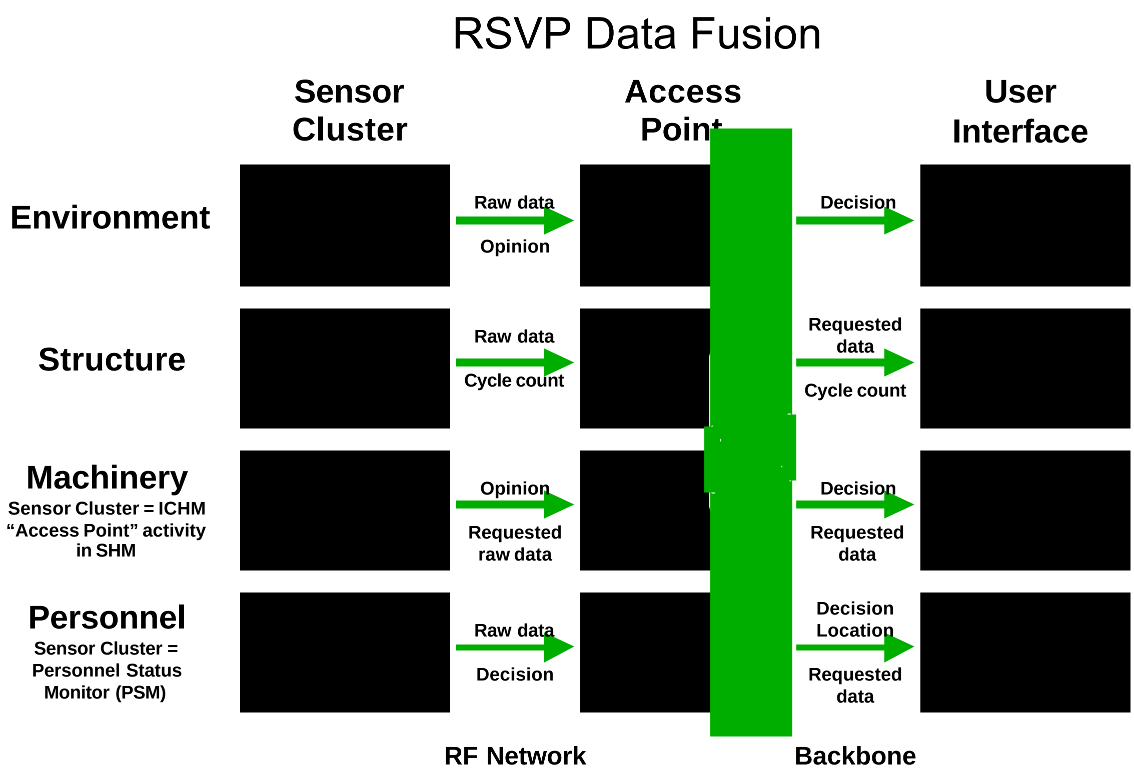

Figure 6 RSVP Data Fusion

RF Architecture

The low power radio frequency (RF) network is described in detailed in the RSVP formal report called “The Radio Network Communication Specification” [ref 13]. The technical report describes the hardware and protocols used to implement the custom, low-power wireless portion of the Reduced Ships-Crew by Virtual Presence (RSVP) system.

The areas to which this document is applicable are the environmental, structural and personnel monitoring functions. Coverage includes all functionality of the Access Point Communications Module (APCM), aspects of the sensor clusters that pertain to system communication, and all functionality of the personnel status monitor from the antenna to the processor-processor interface. The messages being sent throughout the RSVP system are covered by “Integrated Communications Specification Report” [ref 14].

2.1.3 Software

Overview

All communication between the watchstation user interface (WSUI) and subsystems is accomplished by either direct communication with APs or data flow routed through APs. Figure 7 presents an overview of the system hierarchy. The WSUI is designed to provide for interactive viewing of selected system data as well as asynchronous updates due to alarm conditions. The viewing of system data is by hierarchical interaction with graphical screen objects. To facilitate rapid prototyping for the RSVP demonstration effort, two COTS software packages, Sammi (Standard Application Man Machine Interface) and NDDS (Network Data Delivery System), were selected to provide graphical user interface and data communication development environments.

A commercially available graphical interface and communication development package manufactured by Kinesix was chosen to implement the WSUI objects necessary to present preprocessed information from the subsystems. Standards-based Advanced Man Machine Interface (Sammi^{R}) is a client/server and Web-based software development toolkit for creating graphical, networked or embedded applications that are data, event, and command driven. It consists of a graphical editor for creating user interfaces; multiple executable programs that manage the user interfaces and network communicat6ions during runtime; libraries and tools for developing distributed applications that communicate with the Sammi runtime programs and interact with end-users; and libraries and tools for customizing and enhancing the graphical editor and runtime programs. It is designed to facilitate control and monitoring in distributed networks and is suitable for the RSVP application. . Kinesix Corporation located in Houston, TX markets SammiR.

NDDS network middleware software manufactured by Real-Time Innovations (RTI) was selected to meet the requirements for real-time data exchange between APs and to allow both publish/subscribe and client/server request/reply paradigms.

The WSUI to AP interface design requires a definition of the interface between the Sammi and NDDS software as well as the structure of the interface between NDDS and the data for each subsystem.

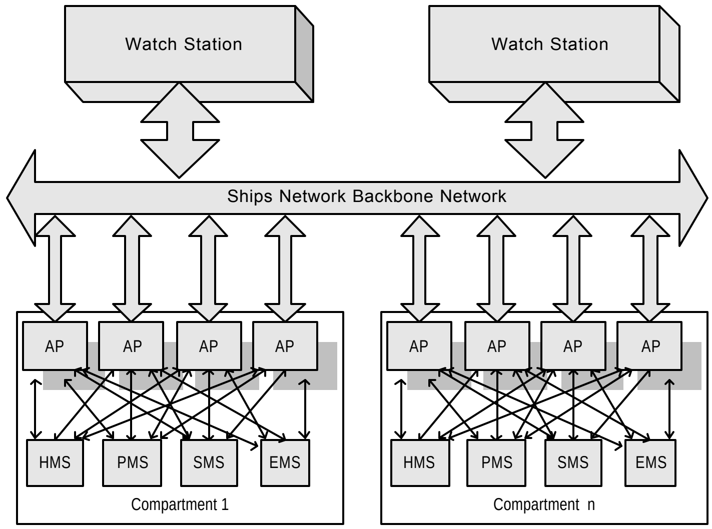

Figure 7 RSVP System Architecture

Sammi

The Sammi environment provides the capability to build graphical user interface (GUI) formats (screens) by using Dynamic Data Objects (DDOs). The interface screens are constructed by dragging and dropping an available set of DDOs. The DDOs contain extensions to allow data and commands to be sent to and from the GUI formats to distributed peer server processes. The Sammi Runtime Environment (RTE) manages the interactions between the DDOs and the server processes. DDOs for both data input and output are provided in the form of integers, floats, strings, charts, buttons, sliders, alarms, etc.
DDOs allow a server process to be specified such that bi-directional data communication can occur between a DDO element and a server located anywhere in the network. The communications are based upon underlying remote procedure calls (RPCs). Input DDOs allow one or more commands to be sent to either a specified server or the Sammi RTE. Commands sent to the RTE provide facilities to add and delete window formats and make layers within a format visible/invisible, among other features. Commands sent to user peer server processes are event driven, and several events can be initiated sequentially based upon DDO inputs such as button clicks. In addition, a peer server process can send commands to the RTE such that the peer server can affect change in the current state of the GUI.

There are two underlying methods to communicate information between a DDO and a server: polled and asynchronous. For each DDO, the protocol is specified as either polled or peer (the asynchronous method is provided by the peer protocol) along with the server name. For polled data, the server only sends DDO updates when requested to do so by the RTE, based on a rate specified by the DDO. The peer data protocol provides for asynchronous updates where the server process drives the update rate. The peer protocol is envisioned as the primary protocol to support the WSUI since much of the RSVP system data will arrive asynchronously. Figure 8 illustrates the Sammi structure.

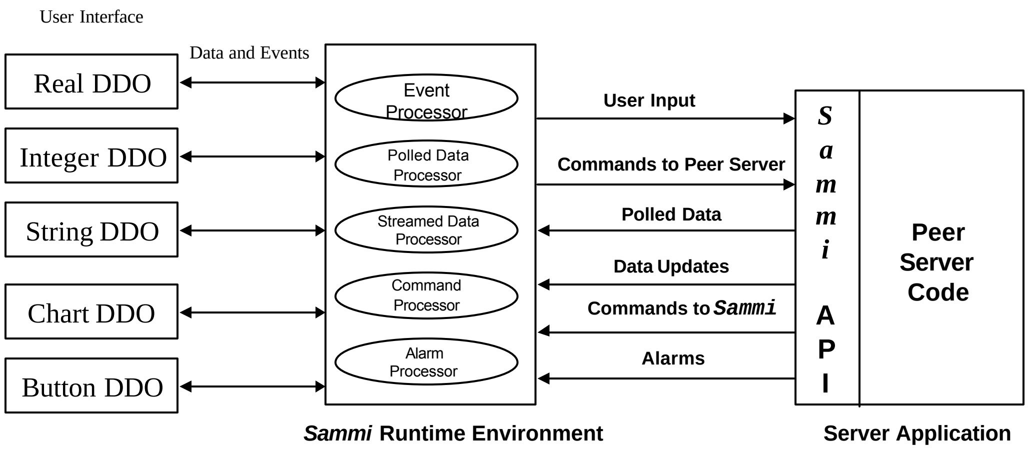

Figure 8 Sammi Structure

NDDS

The NDDS environment provides a middleware component for communications between APs and the WSUI. It provides a standard client/server architecture as well as a publish/subscribe paradigm.
Client and server message object classes can be created anywhere in the network. These disjoint objects communicate by *client objects* initiating requests to NDDS *server objects*. The *client* can wait for the *server* to respond to the request or install a callback to provide notification. This structure is often referred to as a request/reply.

The NDDS publish/subscribe architecture allows publications to be registered over the network. Then the *subscription object* “subscribes to a message” which results in the *publication object* sending its message data to the *subscribing object*. Using this paradigm, no data is actually sent by a *publishing object* until requested by a corresponding *subscription object*. The publish/subscribe protocol allows data to be sent to a client process without the need for the client to issue requests (polling) each time data becomes available.

Sammi/NDDS Interface (SNI)

The Sammi peer server code enabled the mapping of data between Sammi DDO objects and the NDDS message environment and is termed the Sammi/NDDS interface (SNI). The NDDS data is encapsulated in message classes, which provide data input and output via both publish/subscribe and request/reply protocols.

For each NDDS message, a data member called a topic is used to instantiate the object and to identify the particular data structure contained within the message. In addition, separate identifiers are used to identify the particular instance of the message and the location of the data in the network. An NDDS message can then be instantiated for several different topics, each containing different data structures corresponding to particular data sources. The peer server is also designed to facilitate the integration of database message classes to allow the integration of a local database into the watchstation software. Figure 9 illustrates the general interaction between DDOs, the Sammi RTE, the peer server, NDDS messages and database messages.

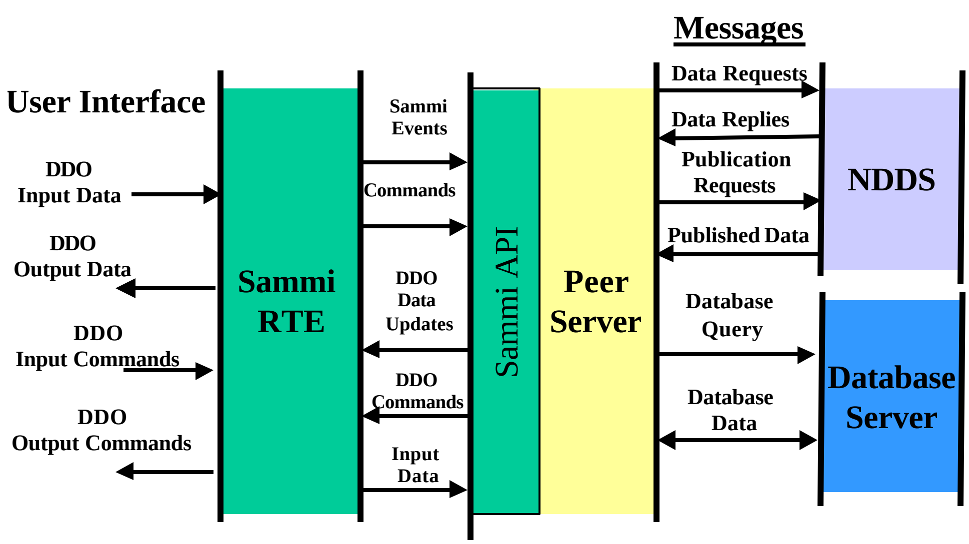

Figure 9 Generalized Sammi/NDDS/Database Message Interaction

Event services handled by the SNI peer server serve as the basis for coordinating the exchange of data between the WSUI and the APs. The event services process are notified in response to Sammi exposure, de-exposure and command events. These events are used to initiate dynamic subscriptions and publications, client/server requests or database requests. The generalized data flow is illustrated in Figure 10 Interface Data Flow.

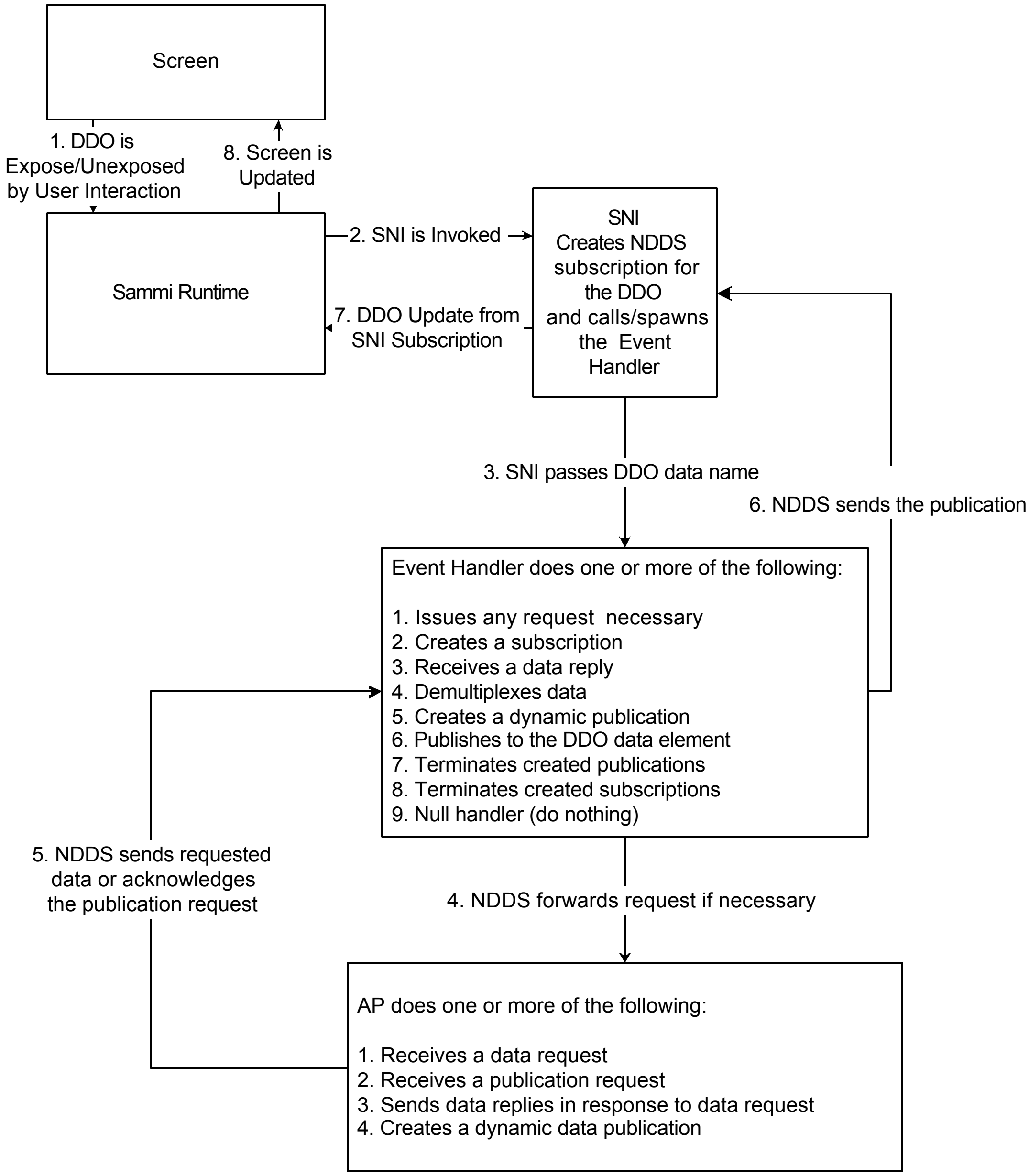

Figure 10 Interface Data Flow

3.0 Demonstrations

3.1 LBES

The purpose of the LBES demonstration was to perform a bottom-to-top Verification and Validation (V&V) of RSVP system component functionality and system integration while installed on the LBES DG-51 class engine plant. Assessment of data validity, data accuracy, and optimum system configuration was not performed in this demonstration. The installation, testing and removal of the RSVP equipment occurred January 19 through February 1, 2001

3.1.1 Primary Goals:

1. Complete subsystem and system integration checkout and operation.
    a. V&V of each subsystem.
    b. All subsystems functioning concurrently.
    c. Subsystems functionally integrated.
2. Validate operation and interface with Navy ship machinery and engine plant systems.
    a. Sensor data acquisition and information fusion of available environmental machinery and structural data.
    b. ICHM and SHM operation and interface/installation on the Allison K17 Generator set.
    c. Wireless data transmission.
    d. HCI functionality utilizing available sensor data and information fusion.
3. Mitigate risk of major demonstrations
    a. Resources to modify or repair will be limited during shipboard tests.

3.1.2 Approach:

1. Install fully constructed and fully functional Environmental Sensor Cluster, Machinery ICHMs and SHMs, and Access Points (APs) into a configuration as similar as possible to the planned CG-47 class installation.
2. Install the Watchstation on the LBES and run the RSVP HCI software.
3. Connect the Watchstation to the APs using an RSVP Local Area Network (LAN).
4. Verify RSVP components function as intended.
    a. SC/ICHM/ SHM sensors acquire data.
    b. SC/ICHM/SHM data fusion performs as designed.
    c. SC/ICHM/SHM data is successfully wirelessly transmitted to APs.
    d. AP data acquisition software functions as designed.
    e. AP data fusion software functions as designed.
    f. APs successfully transmit the correct information to the Watchstation over the LAN.
    g. HCI software receives, displays and reacts to AP information as designed.

3.1.3 Equipment

The LBES demonstration consisted of the following system components:

- Watchstation - 1
- APs - 4
    - APCM - 4
    - Cameras - 4
- Environmental Clusters - 10
- Hubs - 1
- Machinery Health Monitoring System - 1
    - SHM - 1
    - ICHM - 4
    - Instrumentation Box - 1
    - Power Supply Box - 1

3.1.4 Normal Operation Tests

Normal operation tests were executed to verify that the RSVP system and its components were operating in a proper fashion. The following sections describe the various test procedures that were executed.

Environmental Sensor Cluster (ESC)

The ESC is a self-contained unit that senses its local environmental situation, autonomously determines if some level of casualty situation exists, and reports the information to an AP. The ESC monitors the following parameters:

1. Habitation temperature
2. Casualty temperature range
3. Smoke density
4. Carbon monoxide
5. Flooding
6. Hatch closure
7. Compartment pressure
8. Oxygen
9. Humidity
10. Sound

An ESC is considered operating properly if the ESC can successfully perform all of the following scenarios.

Scenario 1: ESC Acquisition

Scenario 2. ESC Data Uplink

Scenario 3. ESC Sound Uplink

Scenario 4. Retrieve ESC Diagnostic Data

Scenario 5. Retrieve ESC Calibration Data

Scenario 6. Retrieve ESC Threshold Data

Scenario 7. Retrieve ESC Location Data

Scenario 8. Retrieve ESC Frequency Data

Scenario 9. Change Single ESC Threshold

Scenario 10. ESC Downlink

Scenario 11. Single ESC Kickoff

Results:

All 10 ESC units passed the 11 scenarios described above. Initially, there was a software error for the Scenario 5: Retrieve Calibration Data test. A solution was determined and implemented. Based on the solution all of the ESC passed all 11 scenarios.

Machinery HMS (ICHM and SHM)

The HMS is considered operating properly if after installed on the SSGTG, the following steps can successfully be performed autonomously;

- The ICHM and SHM boot up when connected to power
- Preinstalled operational configurations are established
- Communications are established between the SHM and ICHM
    - Radio link are established and maintained
    - Communication messages are sent and received

- The ICHM begins data collection, processing and reporting data/information to the SHM.
- The SHM receives information from the ICHM in the form of messages, converts the messages from TCP/IP to NDDS format and transmits to the AP
- The SHM services requests from the Watchstation through the AP and provides data/information in response to operators requests.

General Results:

The four ICHMs and SHM were installed on the K17 SSGTG on the LBES and stepped through a series of tests to verify proper operation and functionality according to the five (5) test requirements identified above. Autonomous operations of the ICHMs and SHM were remotely monitored using several communication and software debug programs that allowed monitoring of the ICHM and SHM operations without direct interaction.

Specific tests and results are as follows;

Installation - install and operate all of the HMS hardware and software on the K17 SSGTG at LBES prior to ship installation to ensure

the proper installation procedures are established and documented

the HMS does not interfere with the SSGTG operation

the HMS operates properly when installed on the SSGTG

Results – NSWCCD code 9332 verified the installation procedures ands installed the HMS hardware. The SSGTG was run over the course of several days, the HMS had no impact on the SSGTG operation. Based on the test and hardware installed, installation procedures were established by the NSWCCD Gas Turbine Life Cycle code in accordance with GTB14.

Power On – test for autonomous boot operation

Results – all ICHMs and SHM booted properly in accordance with preinstalled operating configuration files

Communications Link (SHM to ICHM) – determine if bi-directional communications are reliably and adequately established in the LBES environment

Results – communication between the ICHMs inside and outside the SSGTG module were automatically established and maintained with the SHM located in the RSVP HMS power supply enclosure

Communications Link (SHM to WS) – determine if bi-directional communications, including multiple protocol translations, from the SHM through the AP to the WS and vice versa WS-AP-SHM are reliably and adequately established in the LBES environment.

Results – communication between the SHM and WS *(TCP Server (SHM) to TCP Client (SHM) to NDDS Server (SHM) to NDDS Client (WS))* and WS to SHM communication *(NDDS Client (WS) to NDDS Server (SHM) to TCP Client (SHM) to TCP Server (SHM))* were automatically established and maintained. Publications and subscriptions were started and stopped using the Machine/NDDS interface (MNI) client test program to verify operation

Sensor Connectivity and Operation – verify sensor connectivity and the accurate collection and processing of data from all sensors connected to the ICHMs

Results – Each sensor signal value was compared to locally available readouts for the same parameters. Some variation in electrical parameters were identified. Variations were attributed to filter card settings and adjustment of calibration files – particularly electrical CT's. On-site adjustments were made correcting variations for a majority of the differences. Post LBES tuning of the filter cards will be conducted prior to the Ship install to correct remaining variations.

Sensor/Parameter Data Mapping– verify data/information from the ICHMs and SHM is correctly being sent to the WS

Results – Using the remote DIVA program, parameters and messages from both the ICHMs and SHM were monitored and corroborated with the messages sent to the watchstation. Sensor parameters generated by the ICHMs/SHM and respective messaging were verified.

Data Mapping to Watchstation– similar to that described above, verify data/information from the ICHMs and SHM is correctly being displayed at the WS and operator requests are executed with expected results.

Results – Using the remote DIVA program, parameters and messages from both the ICHMs and SHM were monitored for correct display at the watchstation. The User Interface (UI) was exercised and discrepancies identified. Several were corrected during the course of the test. Remaining corrections are to be accomplished off-site prior to the ship install.

Radio Bit Error Rate (BER) Testing

BER tests were run while the equipment was install on the LBES plant. The initial BER test indicated a BER of 12%. 12% is significantly higher than was expected. A BER of <1%was anticipated. Draper engineers investigated the radio boards and found the new board assemblies had a slightly lower attenuation than the previous assemblies even with the same component. The engineers changed a resistor value to better align the radio. The radio was further tested and found to have BER of <1%. All the radios were modified during the LBES installation period and the BER tests were rerun yielding BER results of <1%.

APs

The AP startup and network software is designed so that AP, when initially turned on, will automatically initiate, configure and establish communications with the other APs in the same compartment. If the a particular AP is the first to be powered on in a compartment it then becomes the Primary AP and controls all the data flow in and out of the compartment.

Results: All 4 APs successfully performed the above requirements

3.1.5 Fault (loss of communications) Recovery Exercises

Fault recovery exercises are design to flex the RSVP architecture and its associated system components and to illustrate many of the unique features of the RSVP system. The following sections describe the various recovery schemes inherent in the RSVP architecture.

APs

Loss Of Network Communications Between AP And WS

Action: The AP will issue a “kick-off” command to all connected Sensor Clusters.

LBES Results: All 4 APs issued a “kick-off” command to the APCM units causing the Sensor Cluster to migrate to other APs.

Loss Communication between AP to APCM

Action: The AP will issue a “kick-off” command to all connected Sensor Clusters.

LBES Results: The serial line connecting the AP and APCM was disconnected and the APCM recognized the lose of communication and issued a “kick-off” message to the Sensor Clusters forcing them to migrate to other APs.

Sensor Clusters

Loss of Communications between Environmental Sensor Cluster and AP

Action: If the Sensor Cluster fails to hear a down link message from the AP 3 consecutive times then the Sensor Cluster will sequence to the next frequency channel in its AP frequency table. The sensor cluster will then try to establish communication with the new AP.

LBES Results: The testing consisted of shutting down APs that were connected to Sensor Clusters. The Sensor Clusters would then migrate to an operational AP. All the Sensor Clusters operated very well during the tests. No Sensor Cluster failed to switch.

Loss Of Communications Between SHM To AP

Action: If communications between the SHM and an AP fails, then the SHM will automatically switch to another AP unit in that given compartment and try to establish communications.

LBES Results: The testing consisted of shutting down APs that were connected to the SHM. The SHM would sense the loss of communication with the AP and then immediately migrate to an operational AP.

Loss of Communications between SHM to ICHM

Action: If communications between the SHM and an ICHM fails, then the SHM after a set period of time will report the communications loss to the Watchstation user interface as a system fault in the alert/alarm region of the Data screen. Additionally, loss of communication between the AP and SHM not associated with a problem with the AP, would result in an SHM communication loss message at the Watchstation.

LBES Results: Testing consisted of powering down each individual ICHM and waiting for the system alert at the Watchstation. Loss of ICHM to SHM communication alert messages were displayed at the Watchstation for each ICHM when it was turned off. Loss of SHM communications was tested by powering down the SHM, resulting in a system alert message at the Watchstation

3.2 At-Sea Demonstration

3.2.1 Introduction

The purpose of the At-Sea demonstration was to perform an evaluation of the RSVP system architecture in an active shipboard environment. The RSVP system was installed aboard the USS MONTEREY (CG-61). The CG-61 conducted a number of at-sea exercises while the RSVP system was on board and operational. RSVP team members evaluated the system while CG-61 was at-sea.

The RSVP system was installed in the Main Engine Room #2 (MER#2). The RSVP system consisted of the RSVP watchstation, 18 environmental sensor clusters, 2 structural sensor clusters, 5 PSM units, 4 APs and 1 HMS (1 SHM and 4 ICHMs). Overall the RSVP system was installed for 110 days. Assessment of data validity, data accuracy, and optimum system configuration was not performed in this demonstration. A number of scripted scenarios were execute to simulate conditions that can not be exercised onboard CG-61, i.e. fire and flooding. All four functional areas were demonstrated while onboard CG-61. The installation, testing and removal of the RSVP equipment occurred February 20 through June 5, 2001. Figure 11, Figure 12, Figure 13 and Figure 14 represent the locations of all the RSVP equipment in MER#2. The RSVP watchstation was location in the Central Control Station (CCS).

3.2.2 Equipment Locations

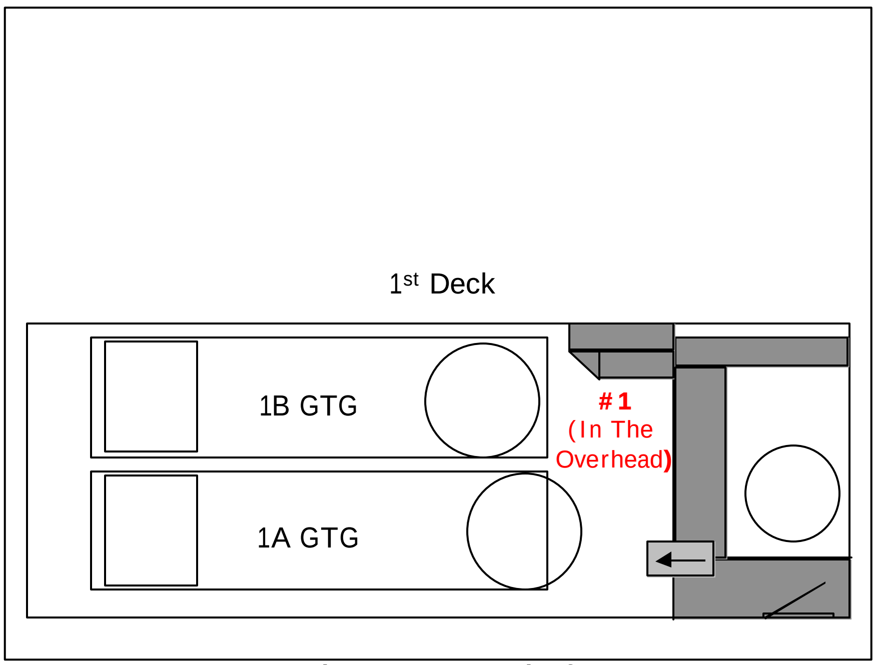

Figure 11 1st Deck of MER#2

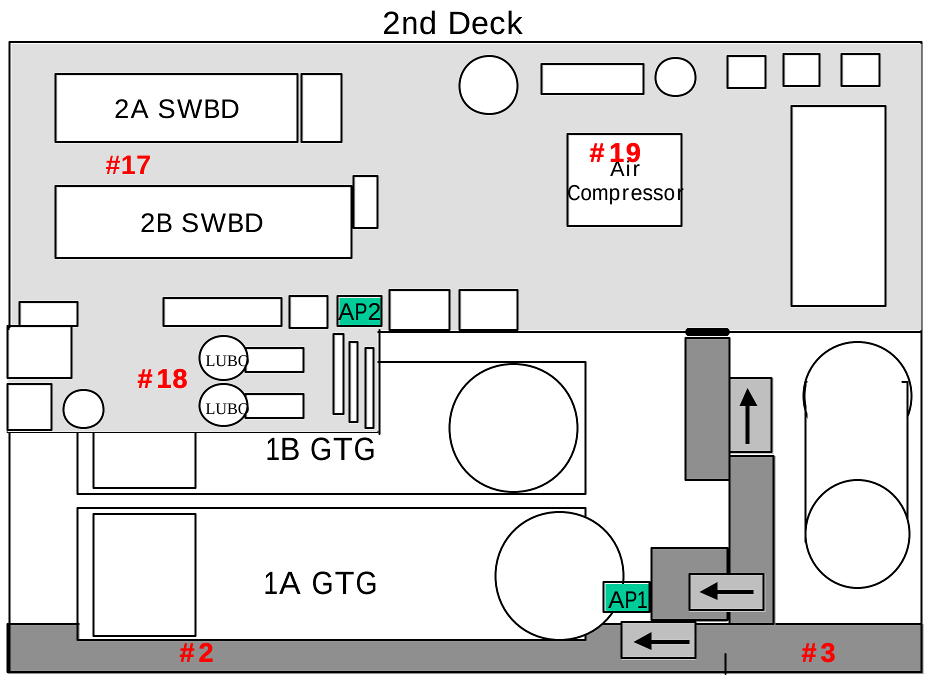

Figure 12 2nd Deck of MER#2

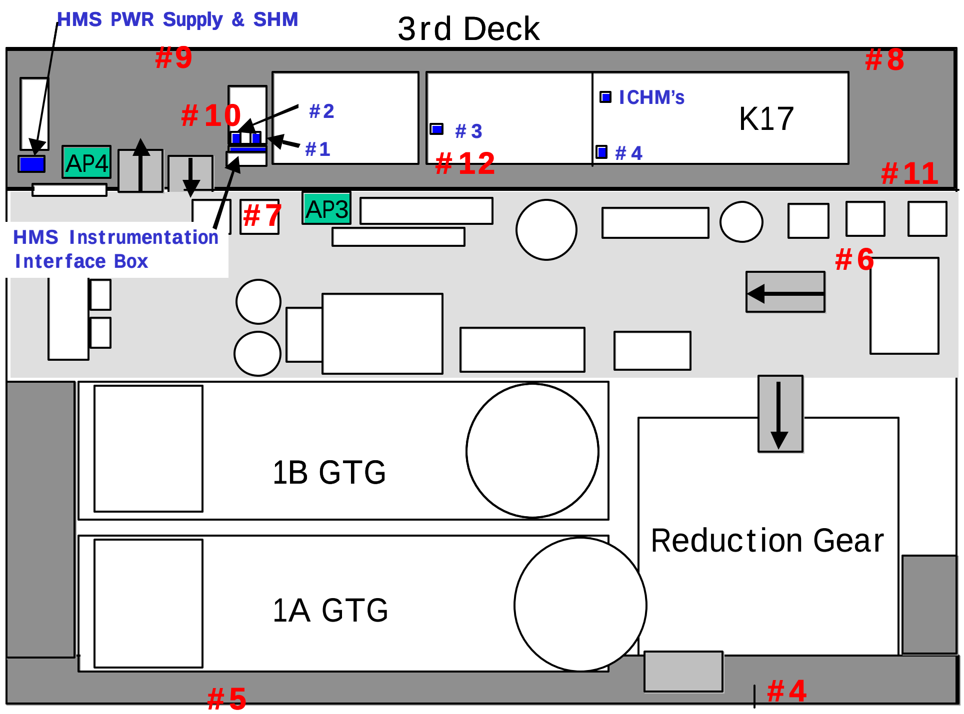

Figure 13 3rd Deck of MER#2

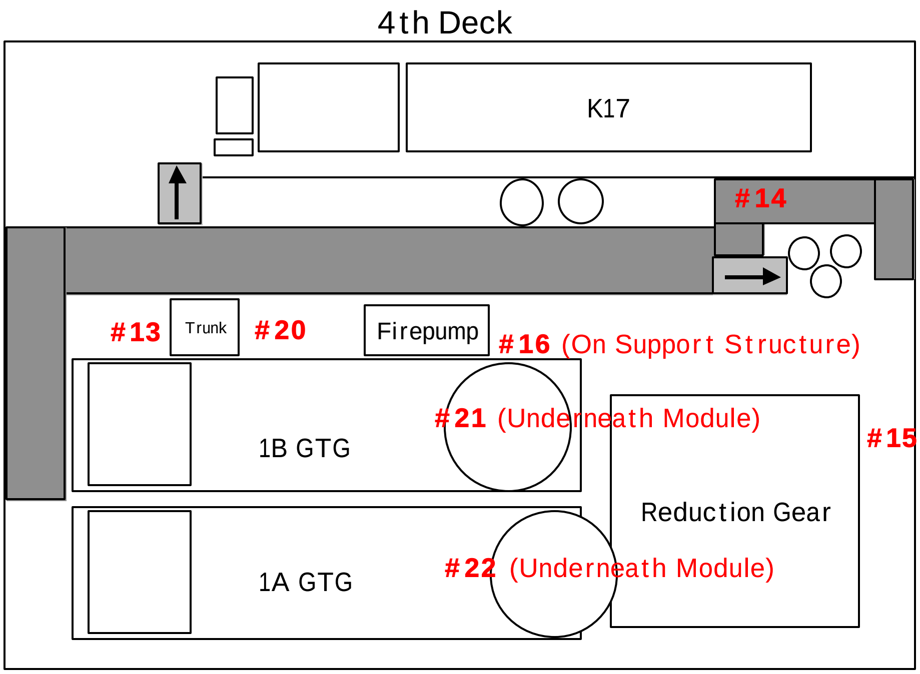

Figure 14 4th Deck of MER#2

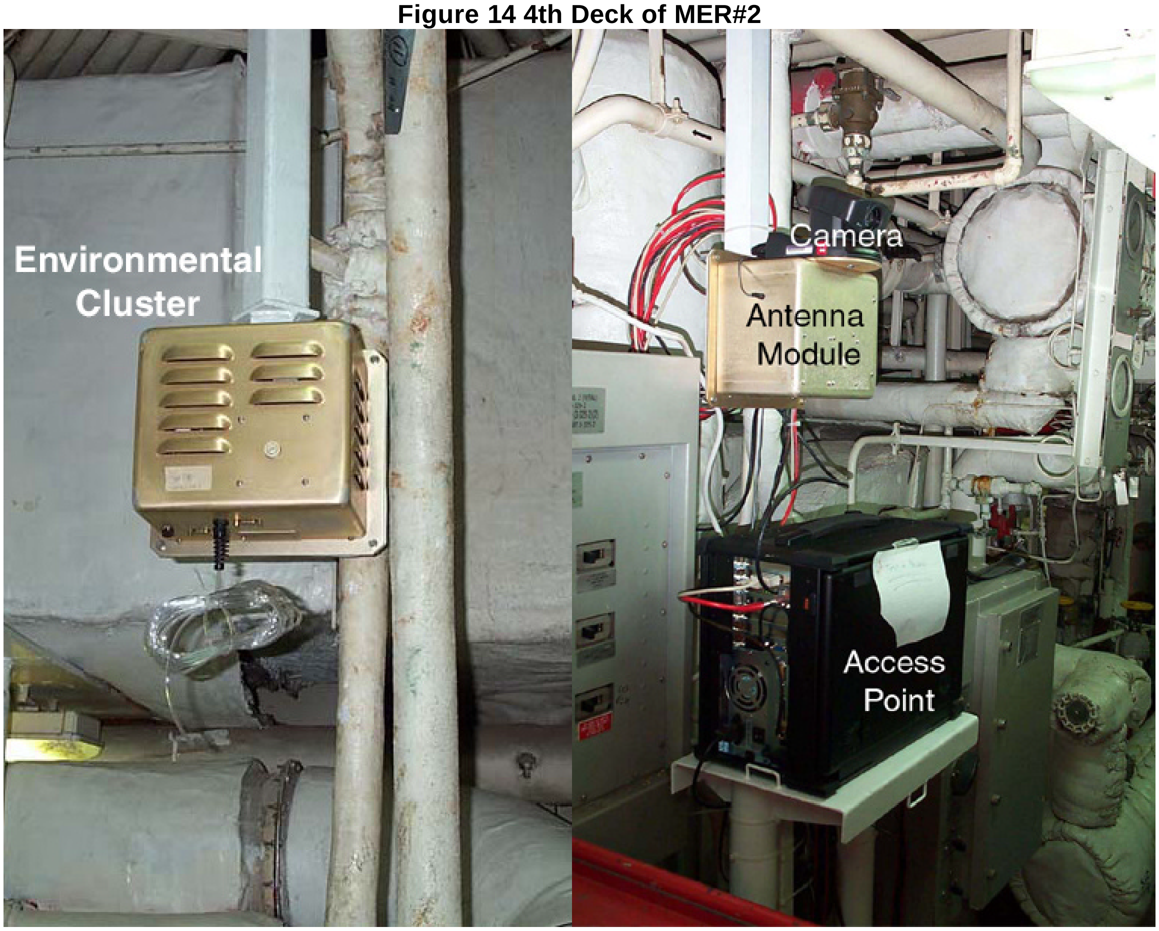

Figure 15 Typical RSVP Installed Equipment Suite

3.2.3